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Contents for October, 1920

NITROGEN ECONOMY IN THE SOIL AS INFLUENCED BY VARIOUS CROPS GROWN UNDER CONTROL CONDITIONS

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During recent years and especially under present conditions, the high price of fertilizer constituents has necessitated in some cases other means of maintaining the fertility of the soil than by applying the customary amounts of commercial fertilizer. The constituent that this paper has to deal with, viz., nitrogen, has become quite expensive; consequently more and more attention is devoted to efforts to maintain the nitrogen supply in the soil through various cultural practices.

One practice, which is a very ancient one, is the growing of various leguminous crops as green manure to be plowed under. That leguminous crops when plowed under always add nitrogen to the soil in excess of that removed by the crop in its growth has apparently seldom been questioned. Likewise, it apparently has generally been taken for granted that a non-leguminous green manure, when turned under, always returns to the soil all the nitrogen that has been removed during its growth.

It is obviously difficult to measure by chemical analysis any slight change in the nitrogen content of a field soil following any treatment due to many uncontrollable factors. The customary method of measuring the effect of a treatment is by comparison in the following crop. In this case evidence does not always show that a leguminous green-manure crop turned under gives a measurable advantage over a non-leguminous green manure, as A. J. Pieters has pointed out in the general summary of his review of American Experiment Station Literature on Green Manures (4). It is further claimed by some that the legume, even when harvested and removed from the soil, leaves as much nitrogen in the roots left behind as was present in the original soil. In other words, it is their claim that the legume in its growth takes from the air, through symbiotic fixation by the legume bacteria, as much nitrogen as is found in that part of the plant above the ground; and that, therefore, when the plant has been harvested the soil has not been robbed but the nitrogen equilibrium has been maintained. On the contrary C. O. Swanson (7) reports that in a number of alfalfa fields under investigation in Kansas which have been cropped continuously for 20 to 30 years, in no field is the nitrogen content equal to that in near-by native sod, except in a few instances in the semi-

arid portion of the state where it is greater. That there are constantly occurring losses of nitrogen in cultivated soil over and above that removed by crops has been brought out by Russell in his monograph "Soil Conditions and Plant Growth" (5). At Rothamsted a small plot of land was isolated in 1870 and thereafter kept free from vegetation by hoeing, disturbing the soil as little as possible. This plot was afterward converted into a lysimeter by surrounding it with a cement wall and underdraining. The drainage water was analyzed daily. During the last twenty years of the experiment, all analyses were made by the same analyst. He found that the soil lost from 1870 to 1905 nitrogen equivalent to 1050 pounds per acre. He further points out that all but 110 pounds of this was recovered as nitrate in the drainage water. The remaining 110 pounds was probably dissipated as free nitrogen or ammonia. Shutt (6) reports a loss of nitrogen in a Saskatchewan Prairie soil after 22 years of cultivation amounting to 2190 pounds per acre. Of this, 700 pounds were recovered in the crop, thus leaving a dead loss of 1490 pounds. Since there is practically no drainage water, probably little of this loss was due to leaching. Lipman and Blair (2) and Mooers (3) in their cylinder experiments both report a gradual decrease in nitrogen both under crops and under fallow. Some of this may be due to leaching, but viewed in the light of the experiment at Rothamsted already mentioned and the work reported upon in this paper, it is safe to conclude that in cropped, cultivated, or otherwise disturbed soil there is certain loss of nitrogen through volatilization. Cultivation is probably responsible for the loss of considerable of the soils' store of nitrogen. The fact can hardly be disputed that the excessive aeration incidental to cultivation causes the oxidation of much organic matter and the consequent liberation of much nitrogen probably in its elemental form. This condition is quite evident in old orchards that have been subjected for a number of years to clean cultivation. The soil gradually becomes "lifeless" through loss of organic matter which must be supplied along with some form of nitrogen in increasing amounts to maintain the original vigor of the trees. Results published by the author (8) show a steady loss in total nitrogen in a number of instances where soils were kept in the laboratory at optimum moisture content and thoroughly stirred and sampled periodically.

PLAN OF WORK

A series of pot experiments were started by the author at Arlington Farm of the United States Department of Agriculture in 1914. The object in view was to make a comparative study of the amount of nitrogen removed from the soil by representative leguminous and non-leguminous crops grown under control conditions, and of the amount of nitrogen recovered in these crops themselves. In brief, the procedure was as follows. The crops were grown in heavy galvanized buckets 15 inches in diameter by 13 inches deep. These buckets hold from 100 to 120 pounds, depending on the character of the soil.

All were housed in a cage built of 1-inch iron pipe covered with wire netting. The buckets were watered to weight daily with distilled water. Detailed description of the construction of the cage and the handling of the containers is given in a paper by the author (9) in the Journal of the American Society of Agronomy.

The soil used was first stirred thoroughly by being screened and then shoveled over several times on a cement mixing-floor. Equal quantities were then weighed out into the containers. A sample of this soil was immediately dried out and retained as a dry check. Fallow checks were kept and treated the same throughout as planted soils. On reaching maturity each crop was harvested close to the surface of the soil, dried, weighed, and ground fine for analysis of total nitrogen. The roots were then screened out of the soil and after being dried and ground were returned and thoroughly mixed with the soil in each container to allow a uniformly representative sample to be taken for nitrogen determination. Samples of soil were then removed and air-dried for analysis. The fallow checks were handled and sampled the same as the cropped soils.

All nitrogen results reported constitute the average of two closely agreeing determinations on 1-gram samples of crops and 10-gram samples of soil. Determinations on crop samples were made by the Gunning method and on soil by the Kjeldahl-Gunning-Jodlbauer method. With both methods the sulfate mixture was used as recommended by Lipman and Sharp (1, p. 648). Nitrates were determined by a modification of the Ulch method. This operation may be briefly described as follows. One hundred grams of air-dry soil is shaken at frequent intervals for half an hour with 285 cc. of distilled water and 15 cc. of aluminum cream. The extract is then filtered off, measured and acidulated with 3 cc. of sulfuric acid. About 2 gm. of iron dust is then added and reduction allowed to take place over-night in the cold. Approximately 8 gm. of heavy magnesium oxide is then added and ammonia distilled off in the usual way. Since only a trace of ammonia was ever found in the soil this was not expelled from the solutions before reduction was started.

In 1914 the soil used was a clay which had been composted with manure and left in a pile for several years previous. A quantity of this soil was limed and portions representing 45 kgm. when brought to the optimum moisture condition were weighed into the containers. The crops grown this season were spring oats, barley, rye, kafir corn, field corn, pearl millet, sugar beets, hairy vetch, field peas, and red clover. All were grown in quadruplicate. The number of plants grown per bucket were four of kafir corn, sugar beets, and millet; three of corn, and ten of all the rest.

In table 1 is shown the yield expressed in grams of dry matter of the entire crop from each bucket.

Table 2 and figure 1 show the yield in grams of nitrogen from each crop and the grams of nitrogen remaining in the soils after the removal of each crop; also the nitrogen found in the fallow check soils and in the dry check which represents the nitrogen in the soil at the beginning of the experiment.

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In table 1 is shown the yield expressed in grams of dry matter of the entire crop from each bucket.

Table 2 and figure 1 show the yield in grams of nitrogen from each crop and the grams of nitrogen remaining in the soils after the removal of each crop; also the nitrogen found in the fallow check soils and in the dry check which represents the nitrogen in the soil at the beginning of the experiment.

TABLE 1

Dry weights of crops harvested

CROP	WEIGHT	AVERAGE WEIGHT
	gm.	*gm.*
Millet	320.0	308.5
	308.0	
	309.0	
	297.1	
Corn	335.5	320.9
	309.3	
	299.2	
	339.5	
Kafir corn	338.9	357.0
	330.8	
	401.5	
	357.0	
Oats	147.7	145.6
	146.7	
	145.9	
	142.2	
Wheat	74.2	72.1
	74.0	
	69.5	
	70.7	
Barley	106.5	118.2
	127.5	
	127.3	
	111.4	
Rye	48.2	43.5
	47.7	
	41.0	
	37.0	
Sugar beets	224.5	232.5
	232.7	
	247.0	
	225.8	
Red clover	83.5	94.0
	96.0	
	101.3	
	95.3	

TABLE 1—*Continued*

CROP	WEIGHT	AVERAGE WEIGHT
	gm.	*gm.*
Vetch	81.2	77.5
	98.0	
	69.0	
	61.9	
Soybeans	329.3	320.2
	300.8	
	313.7	
	337.0	
Field peas	77.7	49.3
	50.1	
	10.0	
	59.3	

From a study of the table and figure the following facts are brought out. Millet and corn removed practically equal amounts of nitrogen from the soil and equal amounts were recovered in the crops; practically as much nitrogen being recovered as was originally present in the soil. Kafir corn, which produced somewhat more dry matter than either millet or corn, also removed more nitrogen from the soil, however in this case not so much was recovered in the crop. Slightly more nitrogen was recovered from oats than from kafir corn. Practically the same amount of nitrogen was recovered from wheat, barley, rye, beets and clover; this amount being less than with the first-named crops, and about 1 gm. less than was originally present in the soil. Somewhat more was recovered from vetch and field peas than in the preceding group. With soybeans more nitrogen was recovered than was originally present.

1. In none of the soils excepting that growing soybeans was as much nitrogen recovered as was present in the original soil represented by the dry check.
2. More nitrogen was lost by some crops than by others.
3. More nitrogen was lost from the fallow soils than from any of the cropped soils. In the latter most of the nitrogen removed by the crops was recovered.
4. Among the legumes only soybean plants contained more nitrogen than was drawn from the soil, considerable nitrogen in this case being fixed from the atmosphere.

In table 3 is shown the nitrogen as nitrate found in the soils after harvest. These results are presented in parts per million and in grams per bucket. On comparing these results with those in table 1 it is evident that in every case the nitrate found after harvest is indirectly proportional to the yield of dry matter. The largest amount of nitrate was naturally found in the fallow check.

TABLE 2

Total nitrogen remaining in the soil and recovered in crops after harvest

CROP GROWN	SOIL		CROPS		TOTAL NITROGEN RECOVERED
	Nitrogen per bucket	Average nitrogen	Nitrogen per crop	Average nitrogen	
	gm.	*gm.*	*gm.*	*gm.*	*gm.*
Dry check	55.14	55.14			55.14
Fallow check	52.84	53.25			53.25
	52.84				
Pearl millet	52.39	52.89	2.12	2.10	54.99
	53.08		2.20		
	53.12		2.06		
	52.98		2.04		
Corn	53.12	52.93	2.21	2.15	55.08
	52.50		1.98		
	52.15		1.99		
	53.94		2.43		
Kafir corn	52.15	51.54	2.66	2.88	54.42
	51.29		2.76		
	51.19		3.41		
	51.53		2.71		
Oats	50.81	52.12	2.50	2.44	54.56
	51.81		2.49		
	53.46		2.40		
	52.70		2.37		
Wheat	53.46	52.47	1.39	1.36	53.83
	52.15		1.40		
	52.26		1.30		
	52.02		1.35		
Barley	51.54	51.84	2.11	2.16	54.00
	53.46		2.26		
	51.19		2.28		
	51.19		2.01		
Rye	54.32	53.26	0.90	0.83	54.19
	53.70		0.91		
	52.46		0.68		
	52.98				
Sugar beets	50.57	50.30	3.54	3.53	53.80
	50.33		3.58		
	51.06		3.52		
	49.23		3.47		

TABLE 2—*Continued*

CROP GROWN	SOIL		CROPS		TOTAL NITROGEN RECOVERED
	Nitrogen per bucket	Average nitrogen	Nitrogen per crop	Average nitrogen	
	gm.	*gm.*	*gm.*	*gm.*	*gm.*
Red clover........	51.06	51..35	2.26	2.45	53.80
	52.74		2.49		
	50.81		2.55		
	50.81		2.50		
Hairy vetch.......	52.50	52.16	2.26	2.18	54.34
	53.32		2.71		
	52.39		1.98		
	50.43		1.77		
Soybeans..........	53.26	52.51	8.93	8.42	60.93
	52.64		7.91		
	52.02		8.10		
	52.02		8.73		
Field peas.........	52.15	52.80	2.03	1.32	54.12
	53.22		1.30		
	54.42		0.30		
	51.43		1.66		

Figure 2 presents a combination of results, viz., the nitrate nitrogen found in the soil after harvest and that actually used by the crops, assuming that the crops obtained their nitrogen as nitrate. Some quite interesting results are brought out here. With but possibly one exception there was a distinct loss of nitrate nitrogen incidental to cropping compared with that found in the fallow check soil. The crops seemed to be divided loosely into groups thus, wheat, oats, barley and rye, which produced comparatively light yields of dry matter, left comparatively large amounts of nitrate in the soil (in this respect wheat and rye left considerably more than oats or barley) and this added to that recovered in the crops make a total of recovered nitrate considerably greater than that from millet, corn and kafir corn. In this latter ground the yield of dry matter was roughly four times greater than in the former, and the nitrate recovered was the least of any of the other crops. Sugar beets might be classed with the preceding group with respect to the nitrate left in the soil, but in the total nitrate recovered they compare closely with the first group. Clover and vetch, which in yield of dry matter exceeded somewhat wheat and did not equal that of oats and barley, left considerably less nitrate in the soil than either of these and the total nitrate recovered was less than for any other except rye. Field peas compared closely with wheat. With soybeans there was a fixation of total nitrogen, so it is uncertain how much was obtained from the atmosphere. However, from table 2 and figure 1

it is seen that there was 2.63 gm. of nitrogen taken from the soil when compared with the dry check. This leaves 5.79 gm. of nitrogen which was obtained from the atmosphere. In figure 2, if this 5.79 gm. were subtracted from the portion of the figure represented in the nitrogen contained in soybeans, we

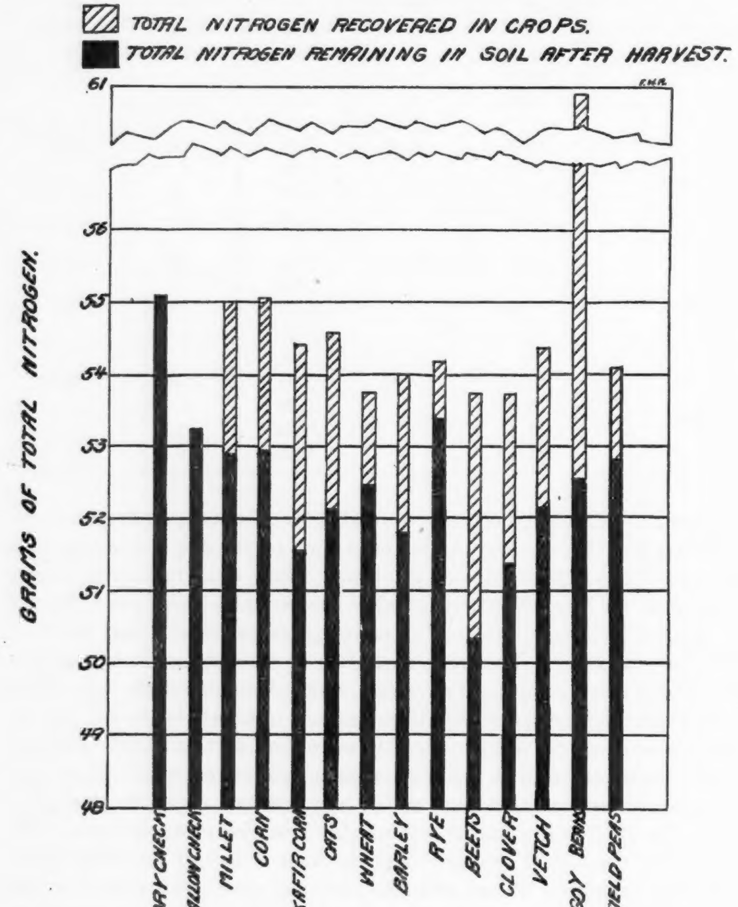

FIG. 1. TOTAL NITROGEN REMAINING IN THE SOIL AND THAT RECOVERED IN THE CROPS AFTER HARVEST

would have left what might represent that portion of the nitrogen in the crop removed from the soil as nitrate together with the nitrate left in the soil, both of which would amount to 3.97 gm., which would also, as in the cases of the other crops, be less than the nitrate formed in the fallow check. This

TABLE 3

Nitrate nitrogen in the soil after harvesting the crops

CROP GROWN	PARTS PER MILLION	AVERAGE	GRAMS	AVERAGE
Fallow check	148.00	146.0	5.09	5.02
	144.00		4.95	
Millet	27.00	24.5	0.93	0.84
	22.00		0.76	
	26.00		0.89	
	23.00		0.79	
Corn	26.00	26.5	0.89	0.91
	31.00		1.07	
	27.00		0.93	
	22.00		0.76	
Kafir corn	16.00	19.00	0.56	0.65
	22.00		0.76	
	19.00		0.65	
	19.00		0.65	
Oats	42.00	60.00	1.44	2.07
	68.00		2.34	
	59.00		2.03	
	72.00		2.48	
Wheat	95.00	97.00	3.26	3.33
	94.00		3.23	
	102.00		3.50	
	97.00		3.34	
Barley	75.00	64.5	2.57	2.21
	62.00		2.13	
	53.00		1.82	
	68.00		2.34	
Rye	92.00	94.00	3.16	3.22
	97.00		3.34	
	87.00		2.99	
	99.00		3.40	
Sugar beets	32.00	31.00	1.10	1.07
	26.00		0.90	
	31.00		1.07	
	35.00		1.20	
Red clover	50.00	43.00	1.72	1.48
	48.00		1.65	
	36.00		1.24	
	38.00		1.31	

TABLE 3—*Continued*

CROP GROWN	PARTS PER MILLION	AVERAGE	GRAMS	AVERAGE
Vetch	50.00	53.00	1.72	1.81
	52.00		1.79	
	54.00		1.86	
	55.00		1.89	
Soybeans	44.00	39.50	1.51	1.35
	37.00		1.27	
	37.00		1.27	
	40.00		1.37	
Field peas	86.00	97.0	2.96	3.34
	89.00		3.06	
	134.00		4.60	
	80.00		2.75	

discrepancy in the amount of nitrate formed in the cropped soils plus that removed by the crop can possibly be explained by one of two suppositions: either nitrification is inhibited by the growth of the crop or nitrification proceeds as rapidly as in the fallow check but some nitrogen is wasted incidental to crop growth. The latter supposition seems to be borne out by table 2 and figure 1, which show a distinct loss of total nitrogen from the soil due to crop growth in every instance except where soybeans were grown. In that case there is no means of knowing if some loss of nitrogen did occur, with nitrogen fixation. Since the fallow check lost considerable total nitrogen, as shown in table 2 and figure 1, possibly more nitrate was formed here than is shown in table 3 and figure 2; in which case the deficit in nitrate recovered from the cropped soils would be greater than is shown.

In table 4 is shown the comparative rate of nitrification in the various soils expressed as the gain in nitrate produced during two weeks' incubation at 28°C. of 100 gm. of soil with 0.2 per cent peptone. These results show some evidence of nitrification having been affected by the residual influence of crops. Nitrification following corn, wheat, beets, soybeans and field peas shows evidence of inhibition, while that following barley and vetch is evidence of stimulation. Following the rest of the crops, millet, kafir corn, oats, rye and clover, the residual influence apparently is neutral.

In 1915 the same general plan was followed except that the experiment was carried in triplicate in three parallel series on as many different types of soils. First, a virgin soil was selected from near Riverside, California. It is a coarse, gravelly loam. The second soil was selected from near Manhattan, Kansas. This is a heavy, black silt loam. The third soil was a clay loam from the Government Arlington Experiment Farm. Chemical analyses of

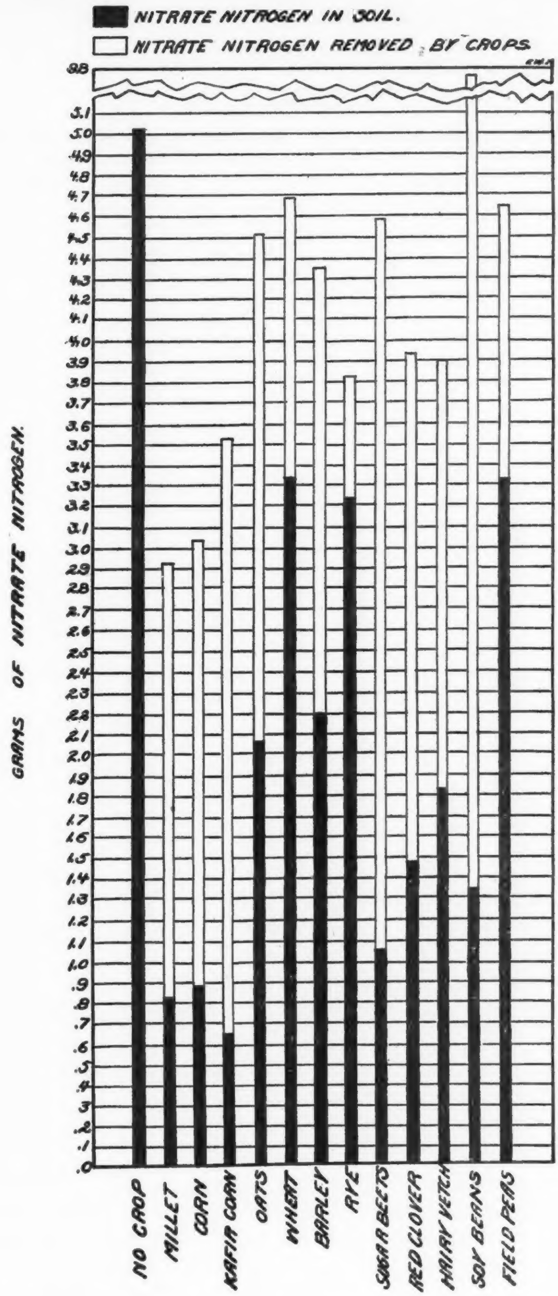

FIG. 2. NITRATE NITROGEN FOUND IN THE SOIL AFTER HARVEST AND THAT REMOVED BY THE CROPS

TABLE 4

Nitrate nitrogen produced during two weeks' incubation of peptone in soil after harvest

CROP GROWN	INCREASE	AVERAGE INCREASE
	p.p.m.	*p.p.m.*
Fallow check	185.00	195.00
	202.00	
Millet	183.00	195.00
	206.00	
	205.00	
	187.00	
Corn	178.00	178.00
	166.00	
	182.00	
	187.00	
Kafir corn	164.00	191.50
	203.00	
	205.00	
	194.00	
Oats	193.00	199.00
	226.00	
	178.00	
Wheat	174.00	181.5
	189.00	
	162.00	
	197.00	
Barley	209.00	220.00
	229.00	
	229.00	
	214.00	
Rye	225.00	191.50
	178.00	
	175.00	
	189.00	
Sugar beets	175.00	186.00
	176.00	
	185.00	
	208.00	
Red clover	.214.00	197.50
	189.00	
	181.00	
	206.00	

TABLE 4—*Continued*

CROP GROWN	INCREASE	AVERAGE INCREASE
	p.p.m.	*p.p.m.*
Vetch	208.00	201.00
	188.00	
	200.00	
	211.00	
Soybeans	190.00	173.50
	191.00	
	162.00	
	162.00	
Field peas	202.00	175.50
	153.00	
	145.00	
	202.00	

these soils made by the Bureau of Soils of the United States Department of Agriculture are given as follows:

	K_2O	CaO	MgO	P_2O_5
	per cent	*per cent*	*per cent*	*per cent*
California soil	1.91	3.13	1.45	0.21
Kansas soil	2.18	1.13	0.86	0.16
Virginia soil	1.72	1.98	0.72	0.19

Since the Kansas and Virginia soils tested acid to litmus they were limed to give a neutral reaction previous to weighing into buckets. The crops grown during this year were oats, barley, kafir corn, crimson clover, soybeans, purple vetch and cowpeas. No attempt will be made to draw any comparisons between these three soils from the standpoint of determining their relative fertility or productiveness, this not being the purpose of the experiment.

The crop yields in grams of dry matter are shown in table 5. In tables 6, 7 and 8 are shown in grams the nitrogen per bucket recovered in the soils after removal of the crops and that recovered in the crops; also the nitrogen in the original soil and that in the samples kept fallow.

In the California soil, as in results already described, considerable nitrogen was lost from the fallow soil. From soil growing oats, kafir corn and vetch, not as much nitrogen was recovered from both soil and crops as was found in the fallow check. Slightly more nitrogen was recovered from barley and clover soils than from the fallow check. The soils under soybeans and cowpeas contained more nitrogen after harvesting the crops than any of the other soils, but somewhat less than the dry check, while the nitrogen found in the

plants was considerably more than was accounted for in that removed from the soil, indicating active fixation.

In the Kansas soil also nitrogen was lost from the fallow. Oats and clover did not remove as much nitrogen from the soil as the fallow. Not as much nitrogen was recovered in the soil and plants in the case of barley and kafir corn as was found in the fallow. Vetch fixed some nitrogen and there was slightly more nitrogen found in the soil than in the dry check, but the amount

TABLE 5

Dry weights of crops harvested

CROP GROWN	CALIFORNIA SOIL		KANSAS SOIL		VIRGINIA SOIL	
	Dry matter	Average	Dry matter	Average	Dry matter	Average
	gm.	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*
Oats	36.0	36.5	38.0	30.2	13.5	12.7
	37.0		14.5		14.5	
	36.5		38.0		10.0	
Barley	35.5	29.5	16.5	26.0	11.5	10.8
	25.5		32.0		10.0	
	27.5		29.5		11.0	
Kafir corn	63.0	65.7	102.0	99.0	121.0	117.7
	74.0		128.0		112.0	
	60.0		67.0		120.0	
Crimson clover	31.5	29.3	35.0	27.2	11.0	12.7
	22.5		23.0		17.0	
	20.5		23.5		10.0	
Soybeans	132.0	127.3	71.0	59.8	61.0	63.7
	132.0		45.0		59.0	
	118.0		63.5		71.0	
Vetch	19.0	13.8	7.5	7.2	2.5	7.7
	12.0		6.5		8.5	
	10.5		7.5		12.0	
Cowpeas	121.0	130.7	125.0	101.2	134.5	159.5
	160.0		83.5		167.5	
	111.0		95.0		176.5	

was easily within the range of analytical error. There was some fixation of nitrogen with cowpeas and practically as much nitrogen was found in the soil as in the fallow soil.

In the Virginia soil there was again considerable loss of nitrogen from the fallow. More nitrogen was recovered from oats and soil than from the fallow. Under barley, clover and vetch more nitrogen was recovered in the soil than in the fallow; but the total in the soil and the plants did not equal that in

the dry check. Not as much nitrogen was recovered from kafir corn and soil as was found in the fallow. Soybeans removed a little more nitrogen than the fallow but no total fixation was indicated. Cowpeas did not remove as much nitrogen as the fallow and considerable total fixation was shown from soil and crop over that present in the dry check.

TABLE 6

Total nitrogen remaining in the soil and recovered in crops after harvest

(California soil)

CROPS CROWN	SOIL		CROPS		TOTAL NITROGEN RECOVERED
	Nitrogen	Average	Nitrogen	Average	
	gm.	*gm.*	*gm.*	*gm.*	*gm.*
Dry check	18.3	18.3			18.30
Fallow check	16.3	16.3			16.30
Oats	15.3	15.3	0.35	0.34	15.64
	15.3		0.34		
			0.33		
Barley	16.5	16.4	0.33	0.29	16.69
	15.3		0.26		
	17.4		0.29		
Kafir corn	15.8	15.4	0.36	0.38	15.78
	15.3		0.43		
	15.0		0.36		
Crimson clover	15.8	16.3	0.80	0.58	16.88
	15.7		0.50		
	17.5		0.43		
Soybeans	16.9	17.4	3.66	3.66	21.06
	17.6		3.76		
	17.6		3.56		
Vetch	15.8	15.9	0.52	0.35	16.25
	16.3		0.27		
	15.7		0.25		
Cowpeas	17.6	17.6	2.81	3.01	20.61
	17.6		3.40		
	17.6		2.82		

To sum up more briefly: In all three types of soil there was a loss of nitrogen under fallow. There was a greater total loss than under fallow in the case of oats, kafir corn, and vetch in the California soil; barley and kafir corn in the Kansas soil and kafir corn in the Virginia soil. Not as much nitrogen was removed from the soil as under fallow in the cases of barley, soybeans

and cowpeas in the California soil, oats, clover, vetch and cowpeas in the Kansas soil, and oats, barley, clover, vetch and cowpeas in the Virginia soil. There was more total nitrogen recovered in the soil and crops than was originally present in the cases of soybeans and cowpeas in the California soil, vetch and cowpeas in the Kansas soil, and cowpeas in the Virginia soil.

TABLE 7

Total nitrogen remaining in the soil and recovered in crops after harvest

(Kansas soil)

CROPS GROWN	SOIL		CROPS		TOTAL NITROGEN RECOVERED
	Nitrogen	Average	Nitrogen	Average	
	gm.	gm.	gm.	gm.	gm.
Dry check	51.5	51.5			51.50
Fallow check	50.4	50.4			50.40
Oats	50.8	50.6	0.78	0.55	51.15
	51.2		0.24		
	49.7		0.62		
Barley	50.4	49.6	0.36	0.53	50.13
	49.0		0.63		
	49.4		0.60		
Kafir corn	48.5	49.1	1.18	0.94	50.04
	49.4		1.05		
	49.5		0.58		
Crimson clover	51.0	50.5	0.87	0.70	51.20
	50.0		0.70		
	50.4		0.53		
Soybeans	49.0	49.1	1.91	1.67	50.77
	50.0		1.32		
	48.4		1.79		
Vetch	52.4	51.7	0.20	0.21	51.91
	51.3		0.19		
	51.4		0.23		
Cowpeas	51.0	50.5	2.74	2.17	52.67
	50.2		1.88		
	50.4		1.94		

In figure 3 is illustrated, as in figure 2, the nitrate nitrogen recovered in the soils after harvest, together with that found in the associated crop, assuming that the nitrogen found in the crop was removed from the soil as nitrate. Here again is shown several instances where either not as much nitrate was formed as that found in the fallow checks, or as much or more was formed and

subsequently lost. In the California soil under oats, barley and kafir corn, not as much nitrate was recovered as in the fallow. Under clover and vetch somewhat more nitrate was recovered than was found in the fallow, although figure 3 shows a distinct loss in total nitrogen in both these instances. Under soybeans and cowpeas there was considerable nitrogen fixation as shown in

TABLE 8

Total nitrogen remaining in soil and recovered in crops after harvest

(Virginia soil)

CROPS GROWN	SOIL		CROPS		TOTAL NITROGEN RECOVERED
	Nitrogen	Average	Nitrogen	Average	
	gm.	*gm.*	*gm.*	*gm.*	*gm.*
Dry check	48.2	48.2			48.2
Fallow check	46.3	46.3			46.3
Oats	46.5	46.6	0.34	0.30	46.90
	46.3		0.33		
	47.0		0.24		
Barley	47.8	47.8	0.31	0.31	48.11
	45.8		0.29		
	49.8		0.34		
Kafir corn	45.1	45.0	1.15	1.17	46.17
	45.4		1.32		
	44.5		1.04		
Crimson clover	46.5	47.2	0.34	0.43	47.63
	47.8		0.58		
	47.2		0.36		
Soybeans	46.3	45.8	1.71	1.88	47.68
	45.1		1.86		
	46.0		2.06		
Purple vetch	47.1	47.1	0.07	0.25	47.35
	47.2		0.29		
	47.0		0.40		
Cowpeas	46.3	47.0	4.60	4.90	51.90
	47.1		5.00		
	47.5		5.10		

figure 3, therefore, it is uncertain how much of this was obtained from the soil as nitrate. In the Kansas soil there was a deficit in the amount of nitrate recovered as compared with that found in the fallow in every case except that of soybeans. In this instance there was also a fixation of nitrogen. In the Virginia soil as in the Kansas soil there is again a deficit in the amounts of

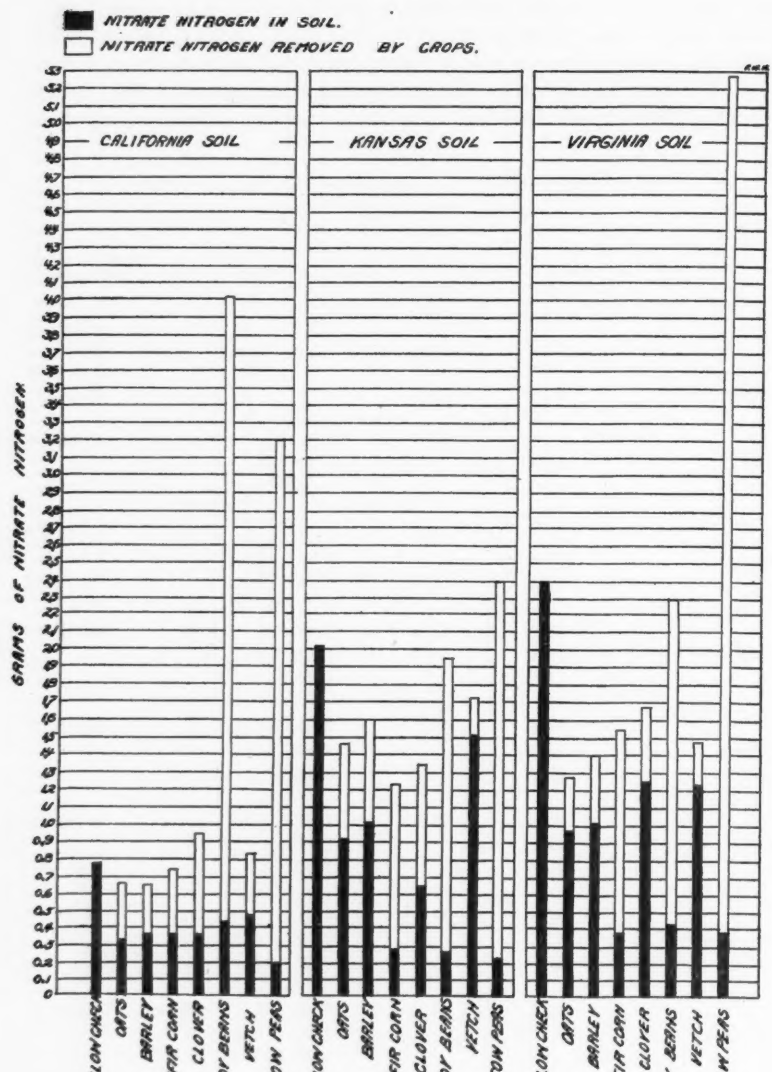

Fig. 3. Nitrate Nitrogen Found in the California, Kansas and Virginia Soils After Harvest and that Removed by the Crops

nitrate recovered in all cases except under cowpeas, where again there was a fixation of nitrogen. Table 9, which shows the comparative nitrifying power or the gain in nitrogen produced during two weeks' incubation of ammonium sulfate (0.139 per cent) with soil at 28°C., seems to indicate that there is more or less crop influence on the formation of nitrate in the soil, thus possibly explaining the results shown in figure 4.

TABLE 9

Nitrate nitrogen produced during two weeks' incubation of ammonium sulfate in soil after harvest

CROP GROWN	CALIFORNIA SOIL		KANSAS SOIL		VIRGINIA SOIL	
	Increase	Average	Increase	Average	Increase	Average
	p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
Fallow check	71.4	71.4	15.2	15.2	261.7	261.7
Oats	78.9	71.1	23.6	25.1	310.0	300.3
	63.4		31.3		299.0	
			20.4		297.0	
Barley	68.1	63.2	7.4	12.0	266.5	271.6
	58.8		13.0		267.3	
	62.8		15.7		281.0	
Kafir corn	51.5	53.3	12.7	8.1	270.1	273.7
	55.3		7.5		275.1	
	53.0		4.2		275.8	
Crimson clover	65.9	66.3	19.5	18.8	304.0	300.2
	65.0		20.3		292.0	
	68.1		16.6		304.5	
Soybeans	64.2	60.9	16.6	18.8	283.0	266.4
	53.3		21.7		249.0	
	65.1		18.1			
Vetch	71.3	70.7	16.8	18.4	293.0	291.8
	70.9		17.4		299.3	
	70.0		21.0		283.0	
Cowpeas	61.0	55.4	14.3	11.1	240.8	233.5
	53.5		15.3		237.8	
	51.7		3.7		221.8	

In 1916 a series of experiments were inaugurated in which the California, Kansas and Virginia soils were used as before; however, in this series the same buckets were cropped for three years and the crops removed without the addition of plant-food in any form. Each season after harvest the buckets were covered to shed rain, and left undisturbed for the winter. The crops grown in each type of soil were as follows: corn, wheat, oats, cotton, soybeans

and cowpeas. In addition, the following rotations were grown in each type of soil: corn, wheat, oats; corn, oats, wheat; soybeans, wheat, oats; soybeans, oats, wheat; and cowpeas, soybeans, cowpeas.

TABLE 10

Dry-weight yields of crops in three-year rotation

(California soil)

1916			1917			1918		
Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Corn	81.0	90.5	Corn	71.0	73.2	Corn	42.0	46.0
	98.0			84.0			50.0	
	97.0			72.0			45.0	
	86.0			66.0			47.0	
Corn	85.0	94.5	Wheat	37.5	34.9	Oats	31.0	29.7
	98.0			27.0			28.0	
	95.0			35.5			28.0	
	100.0			39.5			32.0	
Corn	96.0	93.0	Oats	43.0	46.7	Wheat	20.0	21.2
	85.0			46.5			20.0	
	97.5			47.5			22.0	
	83.5			50.0			23.0	
Wheat	28.5	32.1	Wheat	45.5	44.0	Wheat	22.0	23.5
	33.0			44.0			23.0	
	31.0			44.5			27.0	
	36.0			42.0			22.0	
Oats	39.0	43.6	Oats	57.0	55.6	Oats	27.0	27.2
	44.0			56.0			27.0	
	44.5			53.0			27.0	
	47.0			56.5			28.0	
Cotton	71.0	77.0	Cotton	39.0	37.2	Cotton	13.0	11.7
	69.0			48.0			10.0	
	82.0			30.0			12.0	
	86.0			32.0			11.0	
Soybeans	450.0	378.2	Soybeans	185.0	139.0	Soybeans	40.0	43.7
	360.0			113.0			45.0	
	341.0			185.0			63.0	
	362.0			73.0			27.0	
Soybeans	326.0	345.8	Wheat	41.5	43.6	Oats	33.0	34.2
	342.0			51.5			32.0	
	333.0			37.0			33.0	
	382.0			44.5			39.0	

TABLE 10—*Continued*

1916			1917			1918		
Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Soybeans	289.0	348.5	Oats	62.5	66.4	Wheat	20.0	23.7
	335.0			70.0			23.0	
	434.0			63.5			25.0	
	336.0			69.5			27.0	
Cowpeas	205.0	206.2	Cowpeas	162.0	134.7	Cowpeas	89.0	97.5
	214.0			125.0			115.0	
	187.0			105.0			87.0	
	219.0			147.0			97.0	
Cowpeas	229.0	249.2	Soybeans	122.0	158.0	Cowpeas	112.0	100.0
	352.0			172.0			90.0	
	197.5			180.0			105.0	
	218.5			158.0			93.0	

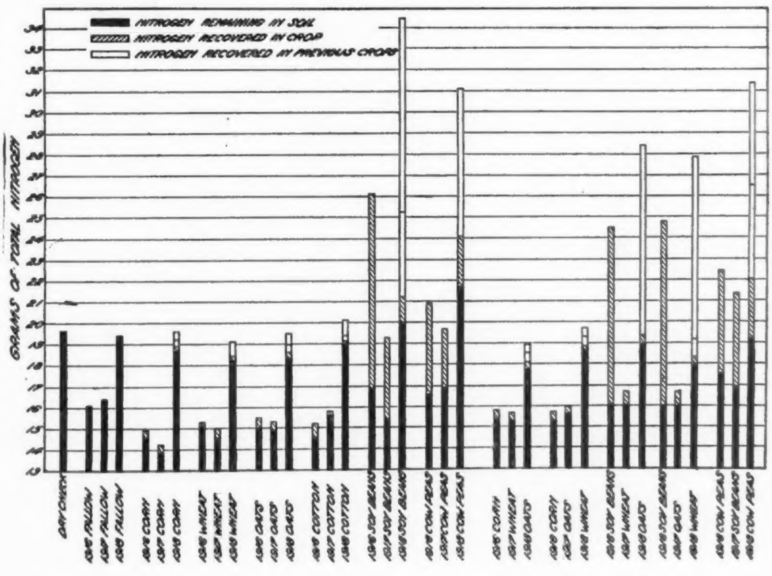

FIG. 4. TOTAL NITROGEN REMAINING IN THE CALIFORNIA SOIL EACH YEAR AND THAT RECOVERED IN THE CROPS

TABLE 11

Dry-weight yields of crops in three-year rotation

(Kansas soil)

1916			1917			1918		
Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average
	gm.	gm.		gm.	gm.		gm.	gm.
Corn	168.0	160.0	Corn	85.0	86.4	Corn	48.0	56.0
	165.0			88.0			52.0	
	167.0			89.0			71.0	
	140.0			83.5			53.0	
Corn	157.5	164.1	Wheat	49.0	46.0	Oats	36.0	31.2
	171.5			43.0			25.0	
	187.0			54.0			31.0	
	140.5			38.0			33.0	
Corn	165.0	163.2	Oats	50.0	52.0	Wheat	12.0	20.0
	173.0			52.0			20.0	
	161.0			46.0			26.0	
	154.0			60.0			22.0	
Wheat	53.0	56.9	Wheat	34.0	39.1	Wheat	26.0	36.0
	55.0			46.0			35.0	
	67.0			48.5			28.0	
	52.5			28.0			35.0	
Oats	85.0	89.2	Oats	56.0	56.5	Oats	39.0	27.7
	83.0			53.0			16.0	
	100.0			54.0			27.0	
	89.0			63.0			37.0	
Cotton	142.0	146.0	Cotton	28.0	36.7	Cotton	32.0	37.0
	178.0			46.0			37.0	
	136.0			28.0			29.0	
	128.0			45.0			50.0	
Soybeans	230.0	216.2	Soybeans	67.0	76.7	Soybeans	35.0	53.0
	208.0			75.0			65.0	
	196.0			97.0			65.0	
	231.0			68.0			47.0	
Soybeans	230.0	216.2	Soybeans	67.0	76.7	Soybeans	35.0	53.0
	208.0			75.0			65.0	
	196.0			97.0			65.0	
	231.0			68.0			47.0	

TABLE 11—*Continued*

1916			1917			1918		
Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Soybeans	209.0	186.0	Wheat	37.5	39.9	Oats	27.0	24.7
	195.0			36.0			25.0	
	209.0			39.0			27.0	
	131.0			47.0			20.0	
Soybeans	285.0	211.7	Oats	40.0	44.0	Wheat	11.0	18.5
	224.0			40.0			19.0	
	147.0			42.0			24.0	
	191.0			54.0			20.0	
Cowpeas	130.0	128.4	Cowpeas	73.0	59.7	Cowpeas	20.0	47.7
	119.5			42.0			65.0	
	138.0			59.0			64.0	
	126.0			65.0			42.0	
Cowpeas	148.0	167.7	Soybeans	68.0	88.5	Cowpeas	32.0	34.0
	192.0			96.0			30.0	
	142.0			103.0			34.0	
	189.0			87.0			40.0	

Tables 10, 11 and 12 show the dry weights of the crops harvested each year. As might be expected, the yield each succeeding year rapidly decreased.

Tables 13, 14 and 15, and figures 4, 5 and 6 show the amounts of total nitrogen remaining in the soil and that recovered in the crops each year. The results shown in the figures represent averages.

In the California soil the results were somewhat different from those found in the other soils in that there was a general tendency in some samples toward an increase in nitrogen each year, while in others there was a decrease the first two years followed by a considerable increase the third year in all samples. In the other two types of soils there was a general decrease each year in all cases.

During this period in the California soil the greatest increase occurred where the same crops were grown in succession, this increase being greater than either under fallow or under rotation. The increase under fallow was less than under rotation. Under soybeans and cowpeas the third year there was more nitrogen found than was in the soil at the beginning of the experiment, as represented by the dry check. Here we have the results of a curious combination of phenomena.

With the exception of the legumes the first two years there was a considerable loss in nitrogen, that is, not as much nitrogen was recovered in the crops as was removed from the soil. Under corn the second year the total loss

TABLE 12

Dry-weight yields of crops in three-year rotation

(Virginia soil)

1916			1917			1918		
Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Corn	319.0 296.0 325.0 349.0	322.2	Corn	85.0 88.0 89.0 83.5	86.4	Corn	80.0 74.0 79.0 75.0	77.0
Corn	304.0 347.0 296.0 354.0	325.2	Wheat	49.0 43.0 54.0 38.0	46.0	Oats	36.0 39.0 37.0 35.0	36.7
Corn	361.0 302.0 324.5 385.0	343.0	Oats	50.0 52.0 46.0 60.0	52.0	Wheat	12.0 11.0 17.0 24.0	16.0
Wheat	65.0 63.0 65.5 58.5	63.0	Wheat	34.0 46.0 48.5 28.0	39.1	Wheat	30.0 21.0 25.0 30.0	26.5
Oats	144.0 157.0 128.0 144.0	143.25	Oats	56.0 53.0	56.5	Oats	36.0 24.0 26.0 33.0	27.7
Cotton	269.0 343.0 250.0 282.0	286.0	Cotton	28.0 46.0 28.0 45.0	36.7	Cotton	25.0 14.0 30.0 30.0	24.7
Soybeans	41.8 367.0 334.0 359.0	369.5	Soybeans	67.0 75.0 97.0 68.0	76.7	Soybeans	63.0 84.0 67.0 83.0	74.2
Soybeans	418.0 367.0 334.0 359.0	369.5	Soybeans	67.0 75.0 97.0 68.0	76.7	Soybeans	63.0 84.0 67.0 83.0	74.2

TABLE 12—*Continued*

1916			1917			1918		
Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average	Crop grown	Dry weight of crop	Average
	gm.	*gm.*		*gm*	*gm.*		*gm.*	*gm.*
Soybeans	354.0	359.2	Oats	37.5	39.9	Wheat	91.0	53.7
	343.0			36.0				
	370.0			39.0			32.0	
	370.0			47.0			38.0	
Soybeans	345.0	347.7	Oats	40.0	44.0	Wheat	22.0	26.7
	329.0			40.0			24.0	
	407.0			42.0			29.0	
	310.0			54.0			22.0	
Cowpeas	251.0	203.7	Cowpeas	73.0	59.7	Cowpeas	15.0	21.7
	172.0			42.0				
	172.0			59.0			23.0	
	220.0			65.0			27.0	
Cowpeas	147.0	212.2	Soybeans	68.0	88.5	Cowpeas	41.0	38.2
	218.0			96.0			41.0	
	257.0			103.0			29.0	
	227.0			87.0			42.0	

amounted to 518 gm. per average bucket. In the case of soybeans and cowpeas, there was an increase in nitrogen the first year, due evidently to symbiotic fixation. This increase was greater under soybeans than under cowpeas. The second year there was still enough nitrogen recovered in the crops almost to make the total of that in the soils and that recovered in the crops equal to that in the dry check. The gain in nitrogen noted the third year in all samples is evidently due to fixation in the soil through biological action. The processes apparently at work more or less simultaneously were denitrification, non-symbiotic and symbiotic nitrogen fixation. Through denitrification there was a total loss of a comparatively large amount of nitrogen from the soil in all samples the first year, with the exception of those under legumes. In some cases during the second year this process still predominated. In other cases including the fallow, free fixation of nitrogen apparently commenced to predominate. The third year this latter process caused the recovery of nearly all the nitrogen that was lost the first year in most cases. Under soybeans and cowpeas the additional process of symbiotic nitrogen fixation was also at work. At the end of the third year there was more nitrogen in the soils under these crops than at the beginning of the experiment, while the total amount of nitrogen for the three years contained in the crops was a clear gain.

In the Kansas soil under the non-legumes with but one exception there was a successive loss of nitrogen each year. In general this loss was progressive,

TABLE 13

Total nitrogen in three-year rotation

(California soil)

1916					1917					1918				
Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in crop	Average	Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in soil	Average	Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in crop	Average
	gm.	gm.	gm.	gm.		gm.	gm.	gm.	gm.		gm.	gm.	gm.	gm.
Corn	14.8	14.5	0.31	0.36	Corn	11.6	13.8	0.35	0.39	Corn	19.2	18.6	0.23	0.90
	15.3		0.39			14.1		0.37			17.9		0.25	
	14.4		0.37			14.8		0.48			19.6		0.23	
	13.6		0.36			14.6		0.38			17.6		0.20	
Corn	15.0	15.4	0.36	0.39	Wheat	15.0	15.3	0.38	0.38	Oats	17.9	17.8	0.28	0.26
	16.4		0.42			15.9		0.30			17.9		0.26	
	15.3		0.38			14.8		0.46			17.9		0.27	
	14.8		0.40			15.7		0.40			17.4		0.33	
Corn	16.6	15.3	0.40	0.41	Oats	16.4	15.6	0.35	0.38	Wheat	18.9	18.7	0.20	0.21
	15.2		0.40			15.3		0.39			19.1		0.22	
	14.8		0.42			15.1		0.41			18.5		0.22	
	14.6		0.41			15.7		0.38			18.5		0.22	
Wheat	15.2	15.1	0.18	0.21	Wheat	15.1	14.5	0.48	0.49	Wheat	17.2	18.2	0.22	0.25
	15.2		0.22			13.4		0.47			17.4		0.23	
	14.4		0.20			14.0		0.48			20.4		0.26	
	15.5		0.24			15.5		0.53			17.9		0.28	
Oats	15.1	15.0	0.46	0.47	Oats	16.0	14.9	0.48	0.45	Oats	18.4	18.3	0.27	0.29
	14.5		0.49			14.0		0.46			18.6		0.31	
	15.3		0.45			14.2		0.39			17.9		0.28	
	15.1		0.47			15.3		0.47			18.3		0.31	

Cotton	14.0	14.5	0.61	0.66	Cotton	14.4	15.5	0.41	0.32	Cotton	18.7	19.0	0.12	0.12
	15.7		0.61			15.3		0.32			20.0		0.13	
	14.2		0.68			17.9		0.30			18.2		0.12	
	14.2		0.73			14.6		0.27			19.1		0.12	
Soybeans	16.2	16.9	10.5	9.21	Soybeans	16.3	15.4	5.65	3.95	Soybeans	19.5	20.0	1.06	1.24
	17.0		8.7			15.1		3.18			20.8		1.42	
	16.2		8.2			14.6		5.00			19.8		1.84	
	18.1		9.4			15.7		1.98			19.8		0.64	
Soybeans	17.9	16.1	7.9	8.40	Wheat	14.9	16.1	0.64	0.62	Oats	20.0	19.0	0.45	0.41
	14.7		7.9			16.3		0.70			18.7		0.36	
	16.8		8.6			16.9		0.57			18.9		0.38	
	15.2		9.2			16.5		0.58			18.3		0.45	
Soybeans	15.7	16.0	7.7	8.76	Oats	15.5	16.0	0.64	0.73	Wheat	19.3	18.1	0.28	0.33
	16.1		8.0			16.8		0.82			18.3		0.33	
	16.1		10.6			16.6		0.64			17.6		0.38	
	16.1		8.8			15.0		0.81			17.4		0.33	
Cowpeas	17.2	16.6	3.8	4.26	Cowpeas	16.2	16.9	3.42	2.84	Cowpeas	22.5	21.7	2.47	2.31
	16.2		4.6			16.8		2.84			20.6			
	17.2		3.8			18.0		2.26			23.1		1.96	
	15.7		4.9			16.5		2.86			20.8		2.51	
Cowpeas	17.0	17.6	4.0	4.95	Soybeans	16.5	17.0	4.20	4.41	Cowpeas	18.7	19.3	3.15	2.79
	19.6		6.5			18.8		5.02			19.5		2.73	
			4.5			16.3		4.65			19.9		2.77	
	16.1		4.8			16.6		3.77			19.3		2.50	
Fallow check	15.5	16.1			Fallow check	17.2	16.4			Fallow check	19.5	19.4		
	18.5					16.0					20.1			
	16.1					15.8					19.1			
	14.2					16.8					19.1			
										Dry check	19.6			

TABLE 14

Total nitrogen in three-year rotation

(Kansas soil)

1916					1917					1918				
Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in crop	Average	Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in crop	Average	Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in crop	Average
	gm.	*gm.*	*gm.*	*gm.*		*gm.*	*gm.*	*gm.*	*gm.*		*gm.*	*gm.*	*gm*	*gm.*
Corn	45.5	46.1	0.83	0.82	Corn	44.0	43.6	0.61	0.63	Corn	42.6	43.0	0.35	0.44
	45.7		0.86			43.2		0.61			42.9		0.40	
	46.6		0.82			42.0		0.67			42.9		0.62	
	46.5		0.76			44.2		0.62			43.5		0.39	
Corn	45.5	44.8	0.74	0.81	Wheat	44.2	43.4	0.86	0.77	Oats	42.5	41.0	0.63	0.53
	43.2		0.83			43.2		0.66			39.5		0.43	
	45.5		0.95			43.7		0.90			41.0		0.52	
	45.0		0.73			42.7		0.68			41.1		0.53	
Corn	45.0	45.6	0.83	0.85	Oats	43.3	44.4	0.86	0.87	Wheat	39.9	40.8	0.20	0.32
	45.0		0.94			44.7		0.66			41.3		0.33	
	45.8		0.79			44.1		0.74			41.0		0.40	
	46.7		0.85			45.5		0.83			41.2		0.35	
Wheat	42.6	43.1	0.98	1.02	Wheat	43.8	44.3	0.56	0.67	Wheat	42.5	42.5	0.42	0.48
	43.3		0.98			44.7		0.84			42.2		0.55	
	43.0		1.18			44.2		0.86			43.8		0.43	
	43.2		0.94			44.6		0.43			41.5		0.54	
Oats	43.5	44.4	1.26	1.24	Oats	43.3	43.8	0.81	0.85	Oats	42.7	42.9	0.58	0.45
	44.7		1.16			46.1		0.81			44.1		0.28	
	44.7		1.28			42.6		0.80			43.9		0.42	
	44.7		1.28			43.2		0.98			41.1		0.52	

Cotton	45.0	45.1	1.46	1.53	Cotton	44.2	44.0	0.44	0.55	Cotton	42.4	42.7	0.57	0.57
	46.1		1.94			43.8		0.63			42.0		0.56	
	44.0		1.28			43.2		0.57			42.8		0.52	
	45.2		1.44			44.7		0.58			43.8		0.64	
Soybeans	46.5	46.2	4.95	4.53	Soybeans	43.3	45.1	1.52	1.68	Soybeans	42.8	43.3	0.86	1.11
	46.4		4.46			44.7		1.66			44.0		1.23	
	46.2		4.05			46.1		2.00			43.6		1.36	
	45.5		4.66			46.3		1.54			42.8		0.99	
Soybeans	45.0	45.6	4.21	3.99	Wheat	44.1	44.9	0.58	0.61	Oats	43.1	42.2	0.42	0.41
	46.1		4.61			44.2		0.54			41.6		0.44	
	45.4		4.56			46.7		0.61			41.5		0.43	
	46.0		2.60			44.7		0.70			42.6		0.36	
Soybeans	45.0	45.9	5.90	4.50	Oats	45.3	45.3	0.61	0.65	Wheat	42.8	42.6	0.20	0.29
	45.0		4.66			45.2		0.61			42.2		0.28	
	46.0		3.35			45.2		0.61			43.0		0.36	
	47.6		4.10			45.6		0.79			42.6		0.32	
Cowpeas	43.2	45.5	2.67	2.42	Cowpeas	45.3	45.6	1.42	1.18	Cowpeas	43.3	44.3	0.38	0.93
	47.1		1.90			47.7		0.85			45.0		1.23	
	46.6		2.60			44.6		1.23			45.0		1.38	
	45.0		2.53			45.0		1.23			43.8		0.73	
Cowpeas	44.5	45.3	2.57	3.02	Soybeans	45.4	44.8	1.60	1.83	Cowpeas	42.6	43.0	0.68	0.68
	44.0		2.35			44.7		1.82			43.7		0.59	
	48.0		2.82			43.8		1.96			42.2		0.65	
	44.8		3.35			45.2		1.94			43.5		0.79	
Fallow check	46.6	46.9			Fallow check	44.6	45.4			Fallow check	43.8	45.1		
	47.5					46.0					45.5			
	46.4					45.2					45.4			
	47.0					45.7					45.6			
										Dry check	47.0			

TABLE 15

Total nitrogen in three-year rotation

(Virginia soil)

1916					1917					1918				
Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in crop	Average	Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in crop	Average	Crop grown	Nitrogen remaining in soil	Average	Nitrogen recovered in crop	Average
	gm.	gm.	gm.	gm.		gm.	gm.	gm.	gm.		gm.	gm.	gm.	gm.
Corn	43.3	43.2	4.17	4.04	Corn	40.4	39.4	2.67	2.24	Corn	38.6	38.6	0.81	0.75
	42.6		3.97			39.0		2.38			38.9		0.78	
	43.5		3.96			39.2		2.12			39.2		0.65	
	43.5		4.06			39.0		1.78			37.7		0.77	
Corn	43.7	43.5	4.36	3.80	Wheat	39.8	40.1	1.11	1.32	Oats	39.6	39.4	0.64	0.67
	44.7		3.86			40.5		1.66			39.4		0.72	
	43.3		3.64			40.6		1.34			39.3		0.68	
	42.3		3.96			39.6		1.18			39.3		0.66	
Corn	44.2	43.5	3.40	2.90	Oats	40.4	39.9	1.91	1.87	Wheat	39.9	38.7	0.19	0.25
	43.5		3.37			39.1		1.95			38.6		0.18	
	44.0		4.44			40.5		2.02			39.3		0.25	
	42.3		4.40			39.7		1.60			37.2		0.37	
Wheat	46.5	46.1	1.30	1.37	Wheat	42.6	42.6	1.39	1.34	Wheat	42.0	41.1	0.52	0.47
	45.2		1.42			42.2		1.02			40.9		0.38	
	46.4		1.41			43.6		1.39			41.3		0.44	
	46.3		1.35			42.0		1.56			40.3		0.53	
Oats	44.0	43.8	3.07	3.03	Oats	40.7	40.4	2.08	2.05	Oats	37.8	38.1	0.60	0.52
	43.3		3.35			40.8		1.93			37.7		0.41	
	44.7		2.65			39.3		2.24			38.2		0.48	
	43.2		3.05			40.7		1.95			38.6		0.61	

Cotton	42.2	43.1	4.55	4.89	Cotton	38.8	38.9	1.94	1.84	Cotton	37.6	38.2	0.71	0.70
	42.4		6.03			38.4		1.66			38.9		0.46	
	44.8		4.29			38.1		1.97			38.4		0.80	
	43.2		4.71			40.0		1.81			37.9		0.85	
Soybeans	44.7	44.2	11.78	9.98	Soybeans	41.3	41.3	6.14	5.98	Soybeans	39.3	39.2	1.55	1.91
	43.7		10.00			40.5		5.18			40.1		2.20	
	44.2		9.05			42.3		5.94			38.2		1.76	
	44.1		9.10			39.8		6.67			39.3		2.15	
Soybeans	44.4	43.8	9.10	8.79	Wheat	40.8	40.8	0.86	1.05	Oats	38.9	38.6	1.77	0.78
	41.2		7.65			41.7		1.18			38.2			
	43.2		9.30			40.8		1.06			38.6		0.60	
	43.4		9.10			39.8		1.10			38.9		0.75	
Soybeans	42.3	42.6	8.85	9.06	Oats	40.4	41.2	1.90	1.89	Wheat	38.2	38.2	0.39	0.47
	42.6		8.75			41.7		1.74			38.6		0.58	
	42.7		11.05			41.0		2.14			37.3		0.50	
	42.7		7.60			41.7		1.78			38.9		0.41	
Cowpeas	42.9	44.6	5.47	4.70	Cowpeas	40.3	40.3	3.23	3.22	Cowpeas	42.2	41.0	0.44	0.62
	42.8		4.77			40.5		3.44			40.3			
	46.6		4.07			40.5		3.14			41.3		0.55	
	46.2		4.49			40.2		3.07			40.3		0.88	
Cowpeas	42.5	43.9	3.80	4.86	Soybeans	39.8	39.9	4.16	4.91	Cowpeas	40.8	38.8	0.86	0.83
	45.1		5.20			39.3		5.18			39.5		0.96	
	45.3		5.70			41.3		4.52			34.5		0.68	
	42.8		4.72			39.3		5.77			40.6		0.81	
Fallow check	48.6	48.0			Fallow	47.8	46.8			Fallow	43.6	45.0		
	47.6					46.7					45.9			
	48.3					46.5					45.2			
	47.5					46.4					45.0			

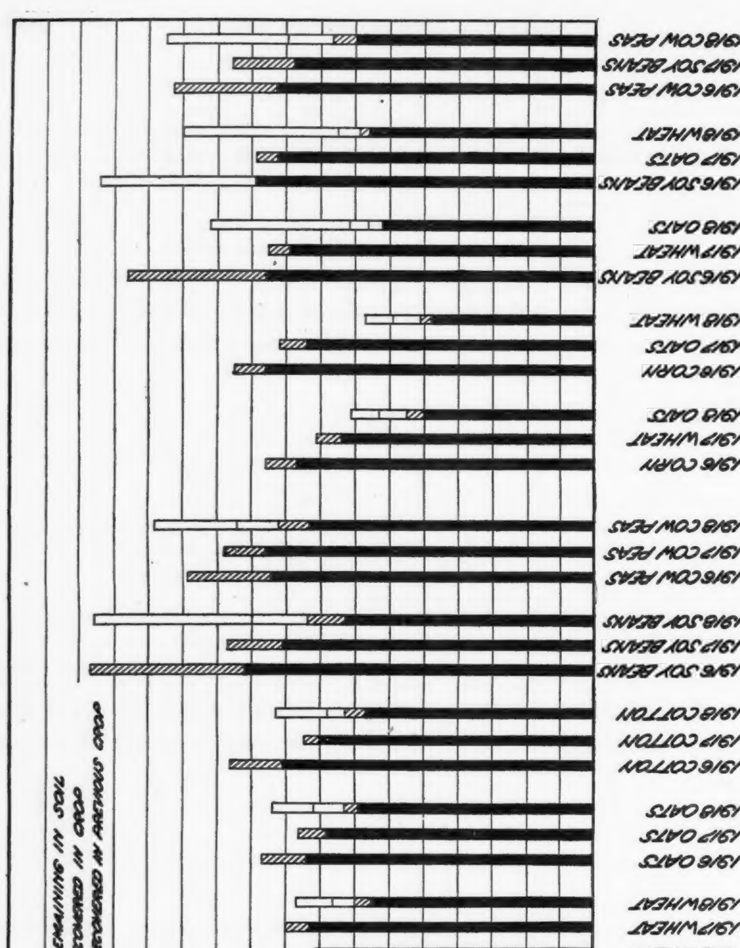

FIG. 5. TOTAL NITROGEN REMAINING IN THE KANSAS SOIL EACH YEAR AND THAT RECOVERED IN THE CROPS

that is, at the end of each season there was less nitrogen in the soil and in the crop than was present in the soil at the end of the preceding year. At the end of the third year the greatest loss was apparent under the corn, wheat, oats, and corn, oats, wheat rotations. Under soybeans and cowpeas there was an increase in nitrogen the first year over that originally present. The second year there was a gain over that present in the soil at the end of the first year. The third year not as much nitrogen was recovered in the soil and crop as was present at the end of the second year.

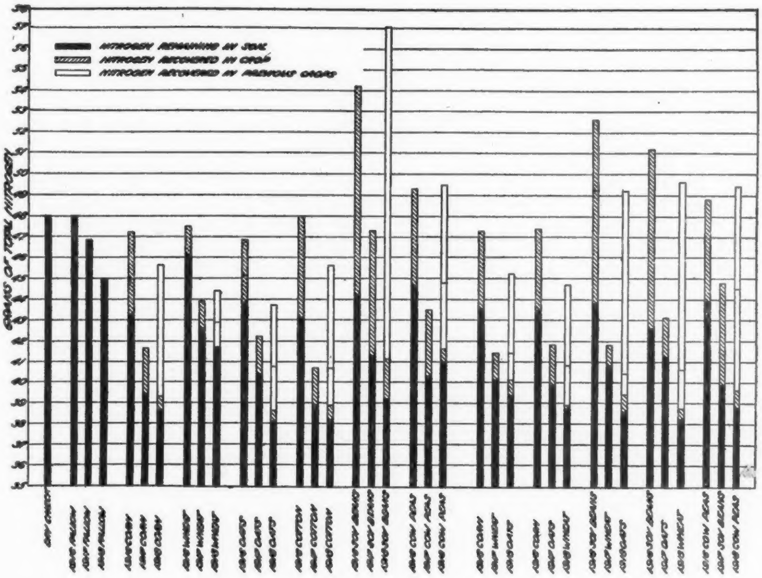

FIG. 6. TOTAL NITROGEN REMAINING IN THE VIRGINIA SOIL EACH YEAR AND THAT RECOVERED IN THE CROPS

In the Virginia soil in all cases there was a progressive loss of nitrogen each year except with the legumes. Under the legumes the first year there was a definite gain. The second year there was more nitrogen recovered in the soil and crops than was in the soil at the end of the first year. The third year there was a loss with soybeans and a slight gain with cowpeas due probably to an increase in nitrogen found in the soil itself.

In tables 16, 17 and 18 are shown the amounts of nitrate nitrogen found in the soils after the removal of the crops and that in the fallows. In figures 7, 8 and 9 are shown both the nitrate nitrogen found in the soils after harvest and the nitrogen recovered in the crops, assuming that the nitrogen in the crops was removed from the soil as nitrate. Here, under all crops, in all soils except where legumes were grown, we find that there was a definite loss

TABLE 16

Nitrate nitrogen in soil after removal of crops

(California soil)

1916			1917			1918		
Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Aver-age
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Corn	0.39	0.34	Corn	0.25	0.21	Corn	0.17	0.18
	0.34			0.17			0.25	
	0.37			0.22			0.12	
	0.28			0.19			0.17	
Corn	0.26	0.26	Wheat	0.28	0.30	Oats	0.25	0.19
	0.27			0.28			0.17	
	0.25			0.31			0.15	
	0.28			0.34			0.17	
Corn	0.28	0.25	Oats	0.12	0.24	Wheat	0.25	0.25
	0.22			0.37			0.25	
	0.23			0.22			0.25	
	0.28			0.27			0.25	
Wheat	0.33	0.47	Wheat	0.37	0.34	Wheat	0.25	0.34
	0.58			0.39			0.38	
	0.55			0.30			0.38	
	0.41			0.31			0.34	
Oats	0.29	0.33	Oats	0.19	0.23	Oats	0.28	0.24
	0.27			0.31			0.17	
	0.41			0.24			0.22	
	0.36			0.19			0.31	
Cotton	0.13	0.12	Cotton	0.16	0.19	Cotton	0.25	0.19
	0.12			0.12			0.17	
	0.14			0.37			0.17	
	0.09			0.12			0.17	
Soybeans	0.50	0.50	Soybeans	0.22	0.22	Soybeans	0.22	0.26
	0.51			0.19			0.31	
	0.62			0.27			0.25	
	0.39			0.19			0.25	
Soybeans	0.40	0.43	Wheat	0.28	0.29	Oats	0.31	0.26
	0.44			0.37			0.25	
	0.47			0.19			0.25	
	0.40			0.34			0.22	
Soybeans	0.45	0.42	Oats	0.12	0.12	Wheat	0.17	0.20
	0.51			0.12			0.17	
	0.32			0.12			0.30	
	0.41			0.12			0.17	

TABLE 16—*Continued*

1916			1917			1918		
Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Cowpeas	0.84	0.82	Cowpeas	0.12	0.44	Cowpeas	0.12	0.22
	1.06			0.57			0.28	
	0.37			0.44			0.35	
	1.00			0.62			0.12	
Cowpeas	0.86	0.76	Soybeans	0.19	0.13	Cowpeas	0.28	0.21
	0.77			0.25			0.17	
	0.87			0.03			0.22	
	0.56			0.16			0.17	
Fallow check	1.12	0.98	Fallow check	1.50	1.42	Fallow check	2.06	1.96
	1.06			1.34			1.94	
	0.96			1.30			1.94	
	0.78			1.53			1.89	

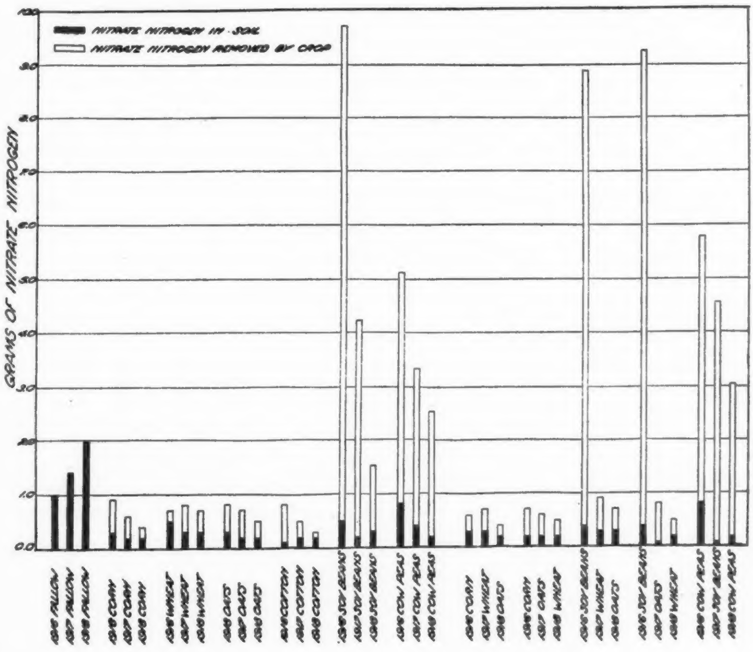

FIG. 7. NITRATE NITROGEN REMAINING IN THE CALIFORNIA SOIL EACH YEAR AND TOTAL NITROGEN RECOVERED IN THE CROPS

TABLE 17

Nitrate nitrogen in soil after removal of crops

(Kansas soil)

1916			1917			1918		
Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average
	gm.	gm.		gm.	gm.		gm.	gm.
Corn	0.34	0.49	Corn	0.27	0.26	Corn	0.18	0.19
	0.51			0.25			0.15	
	0.61			0.27			0.28	
	0.51			0.25			0.15	
Corn	0.64	0.50	Wheat	0.54	0.51	Oats	0.47	0.57
	0.51			0.64			0.74	
	0.17			0.25			0.35	
	0.69			0.63			0.74	
Corn	0.67	0.61	Oats	0.31	0.22	Wheat	0.92	0.57
	0.56			0.34			0.54	
	0.56			0.17			0.47	
	0.67			0.05			0.35	
Wheat	1.26	1.19	Wheat	0.99	0.97	Wheat	1.14	1.01
	1.22						0.84	
	0.91			0.83			0.84	
	1.36			1.08			1.24	
Oats	0.62	0.72	Oats	0.19	0.20	Oats	0.56	0.47
	0.69			0.17			0.54	
	0.59			0.20			0.39	
	1.00			0.26			0.39	
Cotton	0.22	0.15	Cotton	0.37	0.38	Cotton	0.35	0.35
	0.07			0.32			0.35	
	0.15			0.42			0.52	
	0.15			0.42			0.19	
Soybeans	0.47	0.46	Soybeans	0.31	0.32	Soybeans	0.24	0.30
	0.44			0.32			0.39	
	0.47			0.36			0.35	
	0.48			0.30			0.24	
Soybeans	0.37	0.47	Wheat	0.71	0.77	Oats	0.84	0.74
	0.52			0.77			0.79	
	0.53			0.96			0.79	
	0.47			0.63			0.56	

TABLE 17—*Continued*

1916			1917			1918		
Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Soybeans	0.49	0.48	Oats	0.30	0.49	Wheat	1.18	0.99
	0.35			0.44			0.88	
	0.61			0.52			1.02	
	0.47			0.72			0.88	
Cowpeas	0.73	0.76	Cowpeas	0.43	0.53	Cowpeas	0.35	0.26
	0.80			0.54			0.28	
	0.61			0.48			0.14	
	0.89			0.67			0.27	
Cowpeas	0.47	0.54	Soybeans	0.24	0.15	Cowpeas	0.17	0.14
	0.41						0.17	
	0.68			0.05			0.14	
	0.62			0.15			0.07	
Fallow check	2.45	2.54	Fallow check	2.62	2.87	Fallow check	3.16	3.64
	2.76			2.82			3.60	
	2.45			3.25			3.95	
	2.49			2.80			3.87	

of nitrate nitrogen or, better, soluble nitrogen. These results bear out those reported by Lipman (2), Mooers (3), Russell (5), etc. Since no leaching was possible under the conditions of these experiments, this loss must be credited to volatilization of either free nitrogen or ammonia.

Returning to the subject of green manures, the results show an actual loss of nitrogen in all cases where non-legumes are grown and turned under as green manures. It is, of course, obvious that these results cannot be applied directly to field conditions. The inference seems warranted that the loss in nitrogen is due, to a considerable degree, to the thorough aeration given the different experimental soils; and, therefore, the losses of nitrogen that might be expected under field conditions presumably would be much less than indicated in the preceding experiments. Similarly, in field conditions where legumes are grown and turned under, while the general factors of relative gain and loss might be expected to obtain, the actual losses of nitrogen will probably be less.

CONCLUSIONS

Under the conditions of frequent handling with consequent thorough aeration of the experimental soils, the following results have been noted:

1. Cultivation or excessive aeration of a soil causes a loss of total nitrogen.
2. Under certain crops there is an absolute loss of nitrogen in excess of that recovered in the crops.

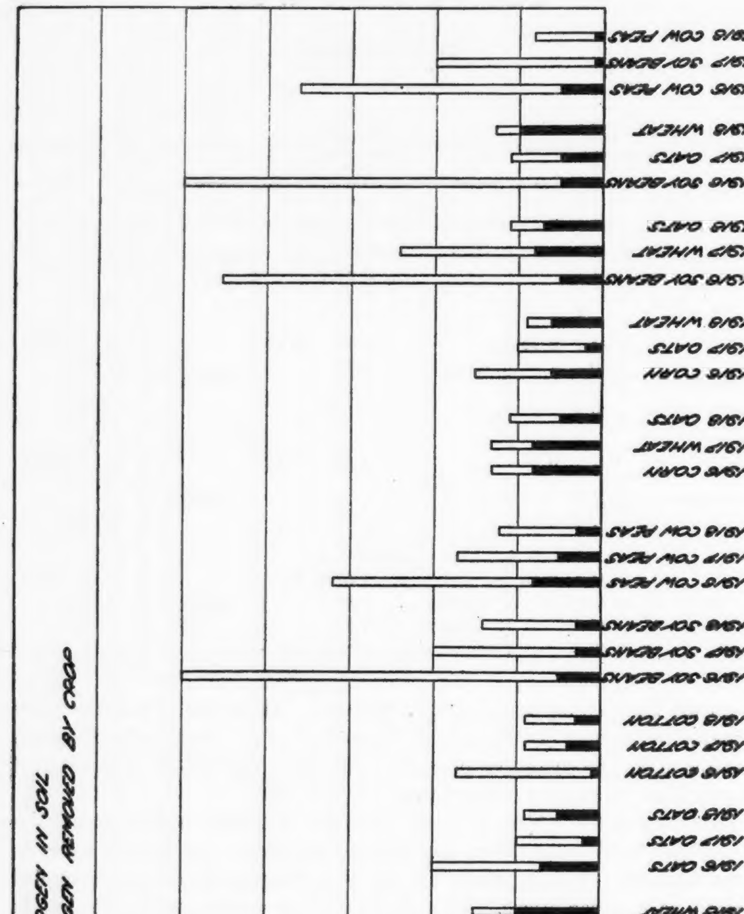

FIG. 8. NITRATE NITROGEN REMAINING IN THE KANSAS SOIL EACH YEAR AND TOTAL NITROGEN RECOVERED IN THE CROPS

TABLE 18

Nitrate nitrogen in soil after removal of crops

(Virginia soil)

1916			1917			1918		
Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Corn	1.69	1.36	Corn	0.18	0.14	Corn	0.25	0.17
	1.42			0.15			0.18	
	1.13			0.25			0.07	
	1.21			0.10			0.18	
Corn	1.50	1.33	Wheat	1.96	1.20	Oats	2.31	1.84
	1.31			0.55			1.20	
	1.21			1.00			1.80	
	1.31			1.31			2.06	
Corn	1.21	1.28	Oats	0.54	0.68	Wheat	1.64	1.78
	1.31			0.63			1.74	
	1.36			0.50			2.09	
	1.23			1.08			1.67	
Wheat	4.55	4.47	Wheat	3.85	4.81	Wheat	5.20	4.71
	5.10			6.90			5.30	
	4.59			4.86			4.35	
	3.63			3.65			4.00	
Oats	2.72	0.74	Oats	1.38	1.54	Oats	1.68	1.71
	2.47			1.36			0.98	
	3.10			1.80			2.31	
	2.66			1.63			1.86	
Cotton	0.77	0.66	Cotton	0.17	0.20	Cotton	0.57	0.66
	0.51			0.20			0.98	
	0.70			0.22			0.55	
	0.65			0.21			0.53	
Soybeans	0.97	0.86	Soybeans	0.29	0.26	Soybeans	0.24	0.21
	0.87			0.24			0.18	
	0.90			0.27			0.18	
	0.70			0.25			0.24	
Soybeans	1.29	1.00	Wheat	1.80	1.44	Oats	2.01	1.88
	1.01			0.99			1.76	
	0.95			2.02			2.09	
	0.75			0.94			1.66	
Soybeans	0.97	0.97	Oats	0.41	0.39	Wheat	1.58	1.51
	1.05			0.32			1.41	
	1.13			1.50			1.38	
	0.75			0.33			1.68	

TABLE 18—*Continued*

1916			1917			1918		
Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average	Crop grown	Nitrate nitrogen remaining in soil	Average
	gm.	*gm.*		*gm.*	*gm.*		*gm.*	*gm.*
Cowpeas	0.55	0.68	Cowpeas	0.88	0.96	Cowpeas	2.01	1.84
	0.70			1.03			2.56	
	0.79			0.95			1.30	
	0.70			0.98			1.50	
Cowpeas	0.83	0.69	Soybeans	0.15	0.17	Cowpeas	0.25	0.42
				0.10			0.40	
	0.77			0.16			0.65	
	0.48			0.28			0.40	
Fallow Check	6.50	6.21	Fallow Check	9.20	8.77			
	6.30			10.00				
	5.90			7.50				
	6.16			8.40				

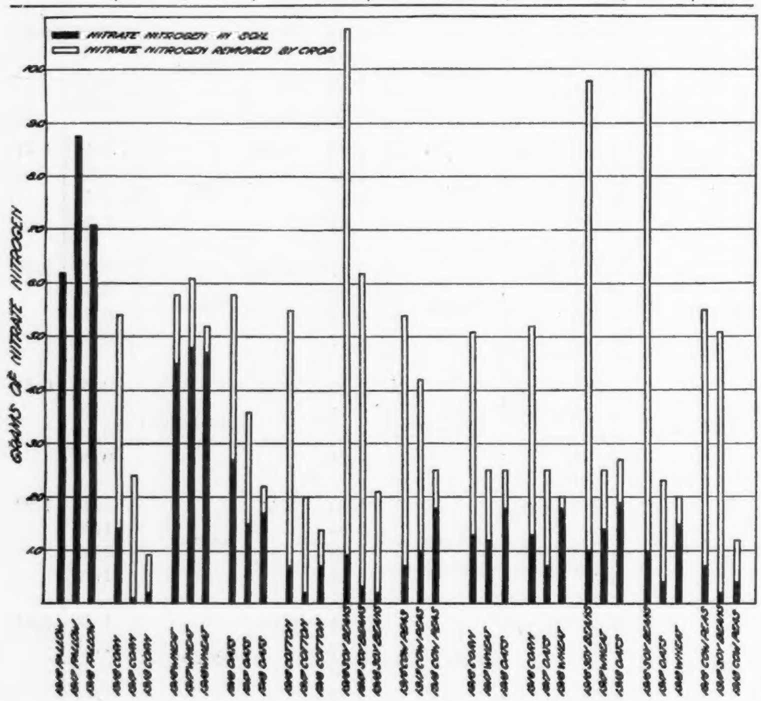

FIG. 9. NITRATE NITROGEN REMAINING IN THE VIRGINIA SOIL EACH YEAR AND TOTAL NITROGEN RECOVERED IN THE CROPS

3. This varies with different crops and different soils.

4. This loss occurs under certain legumes as well as non-legumes.

5. When there is nitrogen fixation with the growth of certain legumes—that is, when there is recovered more than was taken from the soil—this nitrogen is found in the crop above the ground and if this is removed, the soil will have been depleted just as if a non-leguminous crop had been grown and removed.

6. It is recognized that these results are not directly applicable to field conditions. It is not improbable, however, that the changes found to occur under the experimental conditions indicate relatively similar, although perhaps much less marked, changes in the nitrogen content of the field soils when different crops are grown.

REFERENCES

(1) Lipman, C. B., and Sharp, L. T. 1912 Toxic effects of "alkali salts" in soils on soil bacteria: III. Nitrogen fixation. *In* Centbl. Bakt. (etc.), Abt., 2, Bd. 35, p. 647–655.

(2) Lipman, J. G., and Blair, A. W. 1916 Cylinder experiments relative to the utilization and accumulation of nitrogen. N. J. Agr. Exp. Sta. Bul. 289.

(3) Mooers, C. A. 1917 A comparative study of the nitrogen economy of certain Tennessee soils. Tenn. Agr. Exp. Sta. Bul. 118.

(4) Pieters, A. J. 1917 Green manuring: a review of the American experiment station literature. *In* Jour. Amer. Soc. Agron., v. 9, no. 2, p. 62–82; no. 3, p. 109–126; no. 4, p. 162–172.

(5) Russell, E. J. 1912 Soil Conditions and Plant Growth. Longmans, Green and Company, London.

(6) Shutt, F. T. Some characteristics of the Western Prairie soils of Canada. *In* Jour. Agr. Sci., v. 3, pt. 4, p. 335–357.

(7) Swanson, C. O. 1917 The effect of prolonged growing of alfalfa on the nitrogen content of the soil. *In* Jour. Amer. Soc. Agron., v. 9, no. 7, p. 305–314.

(8) Wright, R. C. 1915 The influence of certain organic materials upon the transformation of soil nitrogen. *In* Jour. Amer. Soc. Agron., v. 7, no. 5, p. 193–208.

(9) Wright, R. C. 1916 Growing plants in large containers under control conditions. *In* Jour. Amer. Soc. Agron., v. 8, no. 2, p. 113–116.

CROSS-INOCULATION STUDIES WITH THE NODULE BACTERIA OF LIMA BEANS, NAVY BEANS, COWPEAS AND OTHERS OF THE COWPEA GROUP

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INTRODUCTION

In the spring of 1917, desiring to obtain a reliable source of inoculation for garden beans, three jars of sand, heavily inoculated with soil from a garden where navy and kidney beans were known to have been naturally inoculated, were planted to navy beans, kidney beans and lima beans, respectively. The roots of the navy and kidney beans thus planted were found to be abundantly supplied with nodules, but on the lima beans none were found. The nodules from the navy and kidney beans were crushed in water and returned to their respective jars, the latter then being seeded to lima beans. No nodules were produced although the plants reached a mature age. The third jar, which had contained uninoculated lima beans, was seeded to a mixture of kidney and navy beans, which on examination were found to have numerous nodules in every case.

The results indicated that the bacteria in kidney and navy bean nodules are different from those in lima beans. However, these tests were not made under controlled conditions, and it was desirable to repeat the experiment under sterile conditions, with pure cultures of the several nodule bacteria in question.

EXPERIMENTAL

Local garden soils did not yield a source of inoculation for lima beans, and a "pure culture" from a commercial company failed. Finally, soil which had grown inoculated lima beans was secured from California, nodules were produced by growing plants in sterile sand to which this soil was added and pure cultures obtained by plating out the nodules produced. One culture (1899) came from these original plates, made October, 1917, the other three (1896, 1897 and 1898) were obtained from nodules on a lima bean plant grown in the greenhouse, but the original source of inoculation is the same. These were isolated in February, 1919.

The pure cultures of navy bean bacteria used in the first experiment (1156 and 1157, table 1) were isolated in February, 1919, from a nodule on a navy

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bean plant grown in the greenhouse. Because of the unexpected results of this experiment new isolations were made (1900, 1901, 1912 and 1913) in October, 1919, from a naturally inoculated navy bean plant dug from a local garden. The later isolations were used in the subsequent experiments as indicated, though behaving exactly as did the first two cultures.

Five cultures of cowpea bacteria were used, no. 1867 and 1868 were isolated in May, 1917, and no. 1153, 1869, and 1870 in January, 1919. These were tested out fully prior to these experiments. The plants from which they were obtained were grown in soil in the greenhouse.

In table 1 are reported the results of the first test with lima beans grown in beakers of sterile sand of 600 cc. capacity. In all the experiments sterilized seeds were employed. The methods used are the same as described by Burrill and Hansen (1). This experiment was started August 14 and ended September 7, 1919. Nodules were produced on lima beans by the lima-bean cultures

TABLE 1

Cross-inoculation of lima beans with navy-bean and cowpea bacteria

POT NUMBER	SEEDS PLANTED	SOURCE OF INOCULATION	NUMBER OF SEEDS	PLANTS OBTAINED	NODULE RECORD
1	Lima bean	Cowpea (1869)	4	4	No nodules
2	Lima bean	Cowpea (1153)	4	4	No nodules
3	Lima bean	Navy bean (1156)	4	4	No nodules
4	Lima bean	Navy bean (1157)	4	4	No nodules
5	Lima bean	Lima bean (1896)	4	4	Nodules very large and abundant
6	Lima bean	Lima bean (1898)	4	4	Nodules very large and abundant
7	Lima bean	Check, uninoculated	4	4	No nodules
8	Lima bean	Check, uninoculated	4	4	No nodules

only. Navy bean bacteria did not produce nodules on the lima bean, confirming our preliminary experiments. Cowpea bacteria were included because in a preliminary test lima-bean bacteria produced nodules on cowpeas. But the reciprocal cross failed, as indicated in the tabulated results. This should be carefully noted, as the explanation for it will become apparent in our further discussion.

Another experiment was conducted on a larger scale, four isolations each from cowpeas, lima beans and navy beans, being used. The seeds were planted on December 20, and the plants examined January 12, 1920. In this case the new isolations from a naturally infected navy bean plant were used. The results are shown in table 2, and confirmed the first test.

A similar experiment was tried with cowpea plants, the same cultures being used as before described. The seeds were planted November 22 and the plants examined December 23, 1919. The lima-bean bacteria produced nodules abundantly on cowpea roots, confirming the preliminary test. The cowpea

bacteria produced nodules on the host also, proving the viability of these bacteria. The navy bean cultures failed, however, proving that they were different from either cowpea or lima-bean bacteria. Again attention is directed to the failure of the cowpea cultures to produce nodules on the lima bean.

To demonstrate further the facts brought out, another experiment was started January 15, the results of which appear in table 4. The previous work was confirmed, in that the lima-bean bacteria produced nodules abundantly on cowpea roots, but again cowpea bacteria were unable to inoculate the lima beans as tested up to this time.

TABLE 2

Cross-inoculation of lima beans with navy-bean and cowpea bacteria

POT NUMBER	SEEDS PLANTED	SOURCE OF INOCULATION	NUMBER OF SEEDS	PLANTS OBTAINED	NODULE RECORD
1	Lima bean	Navy bean (1900)	4	4	No nodules
2	Lima bean	Navy bean (1901)	4	4	No nodules
3	Lima bean	Navy bean (1912)	4	4	No nodules
4	Lima bean	Navy bean (1913)	4	3	No nodules
5	Lima bean	Lima bean (1896)	4	4	Nodules very large and numerous
6	Lima bean	Lima bean (1897)	4	4	Nodules very large and numerous
7	Lima bean	Lima bean (1898)	4	3	Nodules very large and numerous
8	Lima bean	Lima bean (1899)	4	4	Nodules very large and numerous
9	Lima bean	Cowpea (1867)	4	4	No nodules
10	Lima bean	Cowpea (1868)	4	4	No nodules
11	Lima bean	Cowpea (1869)	4	4	No nodules
12	Lima bean	Cowpea (1870)	4	4	No nodules
13	Lima bean	Check, uninoculated	4	4	No nodules
14	Lima bean	Check, uninoculated	4	4	No nodules
15	Lima bean	Check, uninoculated	4	4	No nodules
16	Lima bean	Check, uninoculated	4	3	No nodules

Difficulty was experienced in trying to grow navy beans. Several attempts were made, but the germination of the seeds was poor, and those which germinated grew slowly. This was thought to be due to keeping the pots too wet. One-pint mason jars were used, and it was impossible to maintain proper moisture conditions. In order, therefore, to test out the navy bean cultures used, five 1-gallon battery jars of sterile sand were seeded to beans, five seeds being planted in each pot, one each of Early Red Valentine, Golden Wax, and Black Wax and two of common navy beans.

Three of the four cultures used successfully inoculated all the varieties in every case where the seeds germinated. The failure of culture 1900 to produce nodules on any of the five plants cannot be explained. This jar was badly

TABLE 3

Cross-inoculation of cowpeas with navy-bean and lima-bean bacteria

POT NUMBER	SEEDS PLANTED	SOURCE OF INOCULATION	NUMBER OF SEEDS	PLANTS OBTAINED	NODULE RECORD
1	Cowpea	Navy bean (1900)	4	3	No nodules
2	Cowpea	Navy bean (1901)	4	2	No nodules
3	Cowpea	Navy bean (1912)	4	4	No nodules
4	Cowpea	Navy bean (1913)	4	2	No nodules
5	Cowpea	Lima bean (1896)	4	4	Nodules very large and numerous
6	Cowpea	Lima bean (1897)	4	4	Nodules very large and numerous
7	Cowpea	Lima bean (1898)	4	4	Nodules very large and. numerous
8	Cowpea	Lima bean (1899)	4	4	Nodules very large and numerous
9	Cowpea	Cowpea (1868)	4	3	Nodules very large and numerous
10	Cowpea	Cowpea (1868)	4	4	Nodules very large and numerous
11	Cowpea	Cowpea (1869)	4	4	Nodules very large and numerous
12	Cowpea	Cowpea (1870)	4	3	Nodules very large and numerous
13	Cowpea	Check, uninoculated	4	4	No nodules
14	Cowpea	Check, uninoculated	4	3	Several scattered nodules
15	Cowpea	Check, uninoculated	4	3	No nodules
16	Cowpea	Check, uninoculated	4	3	No nodules

TABLE 4

Cowpea bacteria and lima-bean bacteria crossed on cowpeas and lima beans

POT NUMBER	SEEDS PLANTED	SOURCE OF INOCULATION	NUMBER OF SEEDS	PLANTS OBTAINED	NODULE RECORD
1	Cowpea	Lima bean (1896)	4	4	Nodules large and numerous
2	Cowpea	Lima bean (1897)	4	3	Nodules large and numerous
3	Cowpea	Lima bean (1898)	4	4	Nodules large and numerous
4	Cowpea	Lima bean (1899)	4	4	Nodules large and numerous
5	Lima bean	Cowpea (1867)	4	3	No nodules
6	Lima bean	Cowpea (1868)	4	3	No nodules
7	Lima bean	Cowpea (1869)	4	2	No nodules
8	Lima bean	Cowpea (1870)	4	3	No nodules

cracked in sterilization and it was put aside, but after the others had been prepared, it was again added to the series. It is possible that in the change of plans the bacteria were not added.

The results of this test are confirmatory of previous work in that varieties of common beans (not including lima beans) are inoculated by the same strain of nodule bacteria.

In table 6 is given the complete performance record of the navy-bean cultures used. The data reported in tables 1, 2, 3 and 5 are included together with the data from two other experiments not reported in detail. As before stated,

TABLE 5

Navy-bean cultures tested on bean varieties

POT NUMBER	PLANT	VARIETY OF BEAN	SOURCE OF INOCULATION	NODULE RECORD
1	a	Early Red Valentine	Navy bean (1900)	No nodules
	b	Golden Wax		No nodules
	c	Navy bean		No nodules
	d	Navy bean		No nodules
	e	Black Wax		No nodules
2	a	Early Red Valentine	Navy bean (1901)	Failed to germinate
	b	Golden Wax		Nodules large and numerous
	c	Navy bean		Nodules large and numerous
	d	Navy bean		Nodules large and numerous
	e	Black Wax		Nodules large and numerous
3	a	Early Red Valentine	Navy bean (1912)	Nodules large and numerous
	b	Golden Wax		Nodules large and numerous
	c	Navy bean		Nodules large and numerous
	d	Navy bean		Nodules large and numerous
	e	Black Wax		Failed to germinate
4	a	Early Red Valentine	Navy bean (1913)	Nodules small but numerous
	b	Golden Wax		Failed to germinate
	c	Navy bean		Nodules small but numerous
	d	Navy bean		Nodules small but numerous
	e	Black Wax		Failed to germinate

poor germination was the rule with navy beans and in several instances the plants which were obtained were poor and cannot be considered a fair test. As a whole, however, the results are trustworthy. With three of the cultures on the host plant, the results are positive. In no case herein reported did the navy-bean bacteria produce nodules on lima beans or cowpeas.

The data presented demonstrate that the bacteria causing the nodules on the roots of navy beans are different from those on lima beans. The varieties of common beans tested (Early Red Valentine, Golden Wax, Black Wax and common navy bean), however, are inoculated by navy-bean bacteria.

Apparently the limas stand apart. This is the first case known to the authors where different species within a given plant genus require different bacteria.

The data up to this point indicated that cowpea bacteria could not inoculate lima beans but that lima-bean bacteria easily produced nodules on the cowpea. This peculiar failure of the cowpea bacteria to cross on the lima bean could not be satisfactorily explained on any basis known and called for a repetition of the experiments. The purity of the cultures used was proved beyond doubt by all the methods known.

TABLE 6

Performance record of navy-bean cultures

CULTURE NUMBER	SEEDS PLANTED	NUMBER OF SEEDS	PLANTS OBTAINED	DATE EXAMINED	NODULE RECORD
1900	Navy bean	4	1	December 11, 1919	Nodules small but numerous
1900	Cowpea	4	3	December 23, 1919	No nodules
1900	Lima bean	4	4	January 12, 1920	No nodules
1900	Navy bean	4	2	January 12, 1920	No nodules, plant very poor
1900	Navy bean	5	5	February 14, 1920	No nodules
1901	Navy bean	4	2	December 11, 1919	Nodules large and numerous
1901	Cowpea	4	2	December 23, 1919	No nodules
1901	Lima bean	4	4	January 12, 1920	No nodules
1901	Navy bean	4	4	January 12, 1920	Nodules numerous
1901	Navy bean	5	4	February 14, 1920	Nodules large and numerous
1912	Navy bean	4	0		Failed to germinate
1912	Cowpea	4	4	December 23, 1919	No nodules
1912	Lima bean	4	4	January 12, 1920	No nodules
1912	Navy bean	4	1	January 12, 1920	No nodules, very poor plant
1912	Navy bean	5	4	February 14, 1920	Nodules large and numerous
1913	Navy bean	4	0		Failed to germinate
1913	Cowpea	4	2	December 23, 1919	No nodules
1913	Lima bean	4	3	January 12, 1920	No nodules
1913	Navy bean	4	0		Failed to germinate
1913	Navy bean	5	3	February 14, 1920	Nodules small but numerous

Because of our observations as to the relative appearance and growth of nodules on cowpeas and soybeans it was thought that the lima bean, like the soybean, might be slower than the cowpea in demonstrating nodule development. The rapid development of the nodules appears to be related to the nitrogen content of the seed and the rate of growth of the plant.

An experiment was outlined to test the cross-inoculation of cowpea cultures and other cultures of the cowpea group such as those of the partridge pea (*Cassia Chamaecrista*), peanut (*Arachis hypogoea*) and Japan clover (*Lespedeza striata*) on the lima bean.

The data obtained are included in table 7. The plants made a good growth in this experiment. All the cultures produced nodules on the lima bean except *Cassia* and cowpea 1911. The results of this experiment demonstrated that the bacteria of certain plants in the cowpea group could produce nodules on lima beans. The failure in this experiment of the *Cassia* and cowpea culture 1911 to produce nodules on lima beans was in agreement with the performance of certain cowpea cultures in the earlier experiments. It was thought that there might be a difference in the rate of infection between different cultures

TABLE 7

Bacteria of cowpea group crossed on lima bean

JAR NUMBER	SEEDS PLANTED	SOURCE OF INOCULATION	DATE PLANTED	DATE HARVESTED	NUMBER OF SEEDS	PLANTS OBTAINED	NODULE RECORD
34	Cowpea	Cowpea (1456)	March 24, 1920	April 21, 1920	5	1	Large nodules
35	Cowpea	Cowpea (1459)	March 24, 1920	April 21, 1920	5	2	Numerous nodules
36	Lima bean	Partridge pea (1460)	March 24, 1920	April 21, 1920	5	3	No nodules
37	Lima bean	Partridge pea (1461)	March 24, 1920	April 21, 1920	5	3	No nodules
38	Lima bean	Peanut (1462)	March 24, 1920	April 21, 1920	5	3	Large numerous nodules
39	Lima bean	Peanut (1462)	March 24, 1920	April 21, 1920	5	3	Large numerous nodules
40	Lima bean	Peanut (1464)	March 24, 1920	April 21, 1920	5	2	Large numerous nodules
41	Lima bean	Peanut (1465)	March 24, 1920	April 21, 1920	5	2	Large numerous nodules
42	Lima bean	Japan clover (1449)	March 24, 1920	April 21, 1920	5	4	Large numerous nodules
43	Lima bean	Japan clover (1450)	March 24, 1920	April 21, 1920	5	3	Large numerous nodules
44	Lima bean	Cowpea (1911)	March 24, 1920	April 21, 1920	5	3	No nodules
45	Lima bean	Cowpea (1457)	March 24, 1920	April 21, 1920	5	3	Large nodules
46	Lima bean	Check, uninoculated	March 24, 1920	April 21, 1920	5	4	No nodules
47	Lima bean	Check, uninoculated	March 24, 1920	April 21, 1920	5	3	No nodules
48	Cowpea	Check, uninoculated	March 24, 1920	April 21, 1920	5	4	No nodules
49	Cowpea	Check, uninoculated	March 24, 1920	April 21, 1920	5	3	No nodules

or that some condition of these particular jars might be the cause of no nodule production.

In order still further to verify the results obtained, an experiment was conducted that included cowpea, partridge-pea, Japan-clover, peanut and beggar-weed (*Desmodium tortuosium*) cultures of various transfers. *Radiobacter* isolated from cowpea nodules were introduced to test its purity. Some of these were used in the preceding experiments while others were introduced here for the first time.

TABLE 8

Bacteria of cowpea group crossed on lima beans

JAR NUMBER	SEEDS PLANTED	SOURCE OF INOCULATION	DATE PLANTED	DATE HARVESTED	NUMBER OF SEEDS	PLANTS OBTAINED	NODULE RECORD
82	Cowpea	Check, uninoculated	May 1, 1920	May 25, 1920	5	4	No nodules
83	Cowpea	Check, uninoculated	May 1, 1920	May 25, 1920	5	5	No nodules
84	Lima bean	Check, uninoculated	May 1, 1920	May 25, 1920	5	5	No nodules
85	Lima bean	Check, uninoculated	May 1, 1920	May 25, 1920	5	5	No nodules
86	Lima bean	Cowpea (1557)	May 1, 1920	May 25, 1920	5	5	Numerous nodules
87	Lima bean	Cowpea (1557)	May 1, 1920	May 25, 1920	5	5	Numerous nodules
98	Lima bean	Cowpea (1556)	May 1, 1920	May 25, 1920	5	4	Large numerous nodules
99	Lima bean	Cowpea (1558)	May 1, 1920	May 25, 1920	5	4	Large numerous nodules
100	Lima bean	Cowpea (1559)	May 1, 1920	May 25, 1920	5	5	Large numerous nodules
101	Lima bean	Cowpea (1911)	May 1, 1920	May 25, 1920	5	4	Large numerous nodules
90	Lima bean	Partridge pea (1551)	May 1, 1920	May 25, 1920	5	4	Small numerous nodules
91	Lima bean	Partridge pea (1551)	May 1, 1920	May 25, 1920	5	5	Small numerous nodules.
102	Lima bean	Partridge pea (1460)	May 1, 1920	May 25, 1920	5	5	Numerous nodules
103	Lima bean	Partridge pea (1461)	May 1, 1920	May 25, 1920	5	4	Numerous nodules
92	Lima bean	Japan clover (1552)	May 1, 1920	May 25, 1920	5	4	Large nodules
93	Lima bean	Japan clover (1552)	May 1, 1920	May 17, 1920	5	4	Small nodules just started
108	Lima bean	Japan clover (1552)	May 1, 1920	May 25, 1920	5	5	Large numerous nodules
109	Lima bean	Japan clover (1553)	May 1, 1920	May 25, 1920	5	5	Large numerous nodules
94	Lima bean	Peanut (1562)	May 1, 1920	May 25, 1920	5	4	Large numerous nodules
95	Lima bean	Peanut (1562)	May 1, 1920	May 25, 1920	5	5	Large numerous nodules
104	Lima bean	Peanut (1564)	May 1, 1920	May 25, 1920	5	3	Large numerous nodules
105	Lima bean	Peanut (1565)	May 1, 1920	May 25, 1920	5	5	Large numerous nodules
96	Lima bean	Beggar-weed (1555)	May 1, 1920	May 25, 1920	5	4	Large numerous nodules
97	Lima bean	Beggar-weed (1555)	May 1, 1920	May 25, 1920	5	4	Large numerous nodules
106	Lima bean	Beggar-weed (1452)	May 1, 1920	May 25, 1920	5	5	Large numerous nodules
107	Lima bean	Beggar-weed (1452)	May 1, 1920	May 25, 1920	5	5	Large numerous nodules
88	Lima bean	Radiobacter (7)	May 1, 1920	May 25, 1920	5	4	No nodules
89	Lima bean	Radiobacter (7)	May 1, 1920	May 25, 1920	5	4	No nodules
110	Lima bean	Radiobacter (1974)	May 1, 1920	May 25, 1920	5	5	No nodules
111	Lima bean	Radiobacter (1974)	May 1, 1920	May 25, 1920	5	5	No nodules

The complete data are found in table 8. In this experiment, which was conducted under ideal growing conditions, all the cultures produced nodules on the lima bean, except *radiobacter*. The nodules produced by *Cassia* were smaller than those of the other cultures. This experiment confirms the previous one and proves that the bacteria of the members of the cowpea group tested cross on the lima beans.

It was observed that nodule production on the lima bean was slower than that observed on many other plants studied. This observation offered a possible explanation of the negative results obtained with certain of the cowpea and *Cassia* cultures. It will be noted that cultures or transfers which earlier failed to produce nodules, all caused excellent nodule production in these later experiments.

An opportunity to test the relative size of nodules produced under identical conditions of growth on cowpeas and lima beans was presented in connection with other experiments. Lima beans and cowpeas were planted in the same jars of sterile sand. In some treatments bacteria from cowpea cultures and in other treatments bacteria from lima-bean cultures were applied as the inoculation for both kinds of plants. Nodules were larger on the cowpeas than on the lima beans of the same age. The general tendency for larger nodules on the cowpea than on the lima bean, at the earlier stages of growth, is in agreement with similar observations made between the nodule sizes of the cowpea and the soybean. The explanation offered for the difference in nodule size is based upon the relative nitrogen contents of the cowpea and lima bean seeds. The nitrogen content of lima-bean seeds is approximately twice that of the cowpea seeds. This fact coupled with the slower rate of growth of the lima bean would delay the need for atmospheric nitrogen and consequently not hasten the nodule development.

DISCUSSION

These experiments further emphasize the profitable field of investigation that is still open in the study of legume bacteria from the standpoint of cross-inoculation. No fundamental relationship has yet been approached on which any satisfactory explanation for the grouping of legume bacteria for inoculation purposes can be based.

To repeat an earlier statement this work reports the first definite case known to the authors where all the species within a given plant genus are not inoculated by the same nodule bacteria. No reason can be given at this time for the apparent exception, although it is recognized that the metabolism of the lima bean is unlike that of the other beans studied. That other cases of this kind exist seems probable and no doubt further study will discover such.

It had previously been shown (1, p. 135, 136) that cowpeas are inoculated by nodule bacteria from 17 plant species, representing 9 plant genera, several of which (*Cassia*, *Acacia* and *Vigna*) stand widely apart botanically. It has been shown now that the nodule bacteria of another species (*Phaseolus lunatus*, lima bean) of another genus cross-inoculates with the cowpea.

CONCLUSIONS

1. The nodule bacteria of the lima bean (*Phaseolus lunatus*) are distinct from those of the navy and kidney beans (*Phaseolus vulgaris*) for inoculation purposes.

2. The nodule bacteria of lima beans are identical with those of the cowpea group for inoculation purposes.

REFERENCE

(1) Burrill, T. J., and Hansen, R. 1919 Is symbiosis possible between legume bacteria and non-legume plants? Ill. Agr. Exp. Sta. Bul. 202.

THE INFLUENCE OF SOIL REACTION ON THE GROWTH OF ALFALFA[1]

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The application of hydrogen-ion concentration measurements in problems of soil fertility and plant growth is of only recent origin. The importance of such studies has been pointed out by Gillespie (2) who was the first to make use of the hydrogen electrode on a somewhat extensive scale to measure the hydrogen-ion concentrations of soils in suspension. Later Gillespie and Hurst (4) and Gillespie (3) measured the hydrogen-ion concentrations of soil extracts or suspensions in water by a simple colorimetric method, stating that the two methods agreed sufficiently well to show that either one yields approximately correct results. Sharp and Hoagland (12) also discuss the importance of hydrogen-ion concentration measurements in connection with soil fertility problems. Plummer (11), Wherry (13), Knight (8), Joffe (7), and others have made hydrogen-ion concentration measurements of soil suspensions or water extracts of soils either by the use of the hydrogen electrode or by the simpler colorimetric method in connection with soil fertility investigations or in studying other soil phenomena.

Studies relating to the specific effects of the hydrogen-ion concentration on the growth of agricultural plants are indeed limited. Hoagland (6) studied the effect of hydrogen-ion concentration in nutrient solutions on the growth of barley seedlings, and points out that comparatively few experiments have been recorded which bear directly on the growth of the plants of agricultural importance as affected by the acidity or alkalinity of the media in which they were grown.

An attempt has here been made to adjust the soil reaction, as indicated by hydrogen-ion determinations, of a single soil type by the use of sulfuric acid and calcium carbonate and to study experimentally in a very limited way the influence of specific soil reactions upon the growth of alfalfa plants. Alfalfa was chosen for this work because of its economic importance and because of its supposed sensitiveness to soil acidity.

The work was carried out at the laboratory of plant physiology of the New Jersey Agricultural Experiment Station. It is a pleasure here to express thanks to Dr. J. W. Shive for his supervision and interest in the work, also to Dr. S. Waksman for valuable suggestions.

[1] Paper No. 6 of the Technical Series, New Jersey Agricultural Experiment Stations, Department of Plant Physiology.

EXPERIMENTAL PROCEDURE

The soil used in these tests was of the Penn loam type obtained from one of the experimental plots of the New Jersey Agricultural Experiment Station, on which alfalfa was grown. The water extract of this soil gave a hydrogen-ion exponent (pH value) of 6.4. The first step in the preparation of the soil cultures was to establish a range of soil reactions both above and below that of the initial hydrogen-ion exponent value of the soil used. To accomplish this, preliminary tests were made with soil in drinking glasses. Fifty grams of the air-dry soil were placed in each glass. To change the reaction of the soil so as to obtain a series of cultures having a range in hydrogen-ion exponent values below the original value of the soil used (pH 6.4), sulfuric acid (C. P., specific gravity 1.84) in varying amounts was thoroughly mixed with the soil in the glasses after diluting with a sufficient amount of distilled water to give to the soil a moisture content approximately optimum for plant growth. In this way a series of ten cultures was obtained varying in hydrogen-ion exponent values of the soil extracts from 6.4 to 3.0. In another series of ten cultures, precipitated calcium carbonate (99 per cent pure) in varying amounts was added to the soil with thorough mixing in order to obtain a range in the hydrogen-ion exponent values of the soil extracts above the original value. By this method the reaction of the soil in the glasses was changed to give hydrogen-ion exponent values varying from 6.4 to 7.1.

The soil in the glasses was kept at approximately the optimum moisture content for plant growth, and daily determinations were made of the hydrogen-ion concentration of water extracts of the soil in the various glasses. After a period of from 7 to 14 days, the reaction of the treated soil, as indicated by the hydrogen-ion exponents, became constant and no further changes were observed. The water extracts were prepared according to the method recommended and used by Gillespie and Hurst (4). The hydrogen-ion concentrations of the soil extracts were determined by the colorimetric method following the work of Clark and Lubs (1) in the preparation of the standard buffer mixtures and in the use of indicators.

Glazed earthenware pots each having a capacity of 1 gallon were used as containers. Seven pounds of air-dry soil taken from the same lot as that which was used in the preliminary tests with drinking glasses was placed in each container.

The amounts of sulfuric acid or of calcium carbonate to be added to the soil in the containers in order to obtain a series of soil cultures giving the desired range in the hydrogen-ion exponent values, were calculated from the data of the preliminary experiments. The amounts of sulfuric acid added to the soil in the various pots ranged from 15.5 cc. to 0.44 cc. This was always diluted with the distilled water which was applied to the soil to give the desired initial moisture content which was the same in all the pots. The calcium carbonate was thoroughly mixed with the air-dry soil and the distilled water was added

afterward. The amounts of calcium carbonate added to the soil in the various pots ranged from 1.0 to 8.05 gm. per pot. A series of 18 treated cultures and 2 checks, untreated, was thus prepared, giving a range in hydrogen-ion exponent values varying at somewhat irregular intervals from 3.0 to 7.1. The pots were allowed to stand in the greenhouse unplanted until the hydrogen-ion exponent values of the soil extracts remained approximately constant, as indicated by the tests made from time to time.

The soil in each of the pots was planted with 50 seeds and after germination some of the young plants were removed, leaving 10 plants in each pot. The cultures were weighed every other day and at each weighing the water lost by evaporation from the surface of the soil and by transpiration was restored by the addition of distilled water. The cultures were conducted from October 28, 1919 to May 5, 1920. Hydrogen-ion concentration measurements of the soil from each culture were made at regular intervals throughout the growth period; in all 12 determinations for each culture in the series were made. At the end of the growth period the plants were harvested, and the dry weights of tops, per cent of nitrogen in the tops, and the relative number of nodules on the roots of the plants from the various cultures were determined.

EXPERIMENTAL RESULTS

The numerical data showing the relation between the soil reaction as indicated by the hydrogen-ion exponent values of the water extracts of the soil samples taken at regular intervals during the growth period, and the various quantitative plant measurements are presented in table 1. In the table are given four columns of pH values, three of which represent the results of tests made at the beginning, near the middle, and at the end of the growth period, while the fourth column gives the averages of all the determinations (12 in number) for each culture. These columns of pH values serve to show the general trend of the change in the reaction of the soil in the various cultures during the growth of the plants.

A comparison of the average pH values with the corresponding percentages of germination brings out the fact that the germination of the alfalfa seed was greatly reduced in the cultures showing average pH values of the soil extracts below 4.5. In culture 1, the soil extract of which gave a pH value of 3.3, no germination occurred. As the hydrogen-ion concentration of the soil decreased from a pH value of 3.5 to one of 4.5, a gradual increase in the percentage of germination is shown. However, germination was remarkably constant in cultures showing a range in the average hydrogen-ion exponent values from 4.5 to 7.0.

The data of table 1 show very clearly that alfalfa may grow fairly well in a very acid soil, as is indicated by the growth of the plants in culture 4. The soil in this culture gave an average hydrogen-ion exponent value of 3.8. While only three plants survived this high hydrogen-ion concentration, the fact

remains that these three plants, after becoming established, made very good growth, and this is also true of the four surviving plants in culture 5, and the five surviving plants in culture 6. It is to be emphasized, however, that in these cultures and also in those with soils giving somewhat higher hydrogen-ion exponent values, the plants experienced difficulty in establishing themselves. During the first two months the plants were retarded in growth, making slow

TABLE 1

Numerical data showing the relation of soil reaction to germination, nodule formation, dry-weight yields of tops, and nitrogen content of alfalfa tops grown from October 29 to May 5 in soil cultures

CULTURE NUMBER	pH VALUES OF WATER EXTRACTS OF SOIL				GERMINATION	NODULES PER PLANT RELATIVE TO THOSE OF CULTURE 4 AS UNITY	DRY WEIGHT OF TOPS (10 PLANTS)	TOTAL NITROGEN IN TOPS
	October 28, original	January 28	May 5, final	Average of all (12) tests				
					per cent			*per cent*
1	3.0	3.5	3.5	3.3	0			
2	3.2	3.6	3.6	3.5	5			
3	3.4	3.8	3.8	3.6	28			
4*	3.6	3.8	4.2	3.8	60	1	3.7	1.85
5*	4.0	3.9	4.6	4.0	85	4	4.9	2.44
6*	4.1	4.2	4.8	4.3	90	2	6.2	2.94
7	4.4	4.4	5.0	4.5	94	1	6.7	2.89
8	4.8	5.0	6.0	5.0	94	3	6.2	3.08
9	5.6	5.8	6.0	5.7	94	3	6.4	3.03
Check	6.4	6.2	6.4	6.3	92	4	6.8	3.21
11	6.4	6.6	6.2	6.3	94	5	6.7	3.58
12	6.4	6.6	6.4	6.4	95	5	6.6	3.53
13	6.6	6.6	6.6	6.5	94	5	8.4	3.28
14	7.0	6.6	6.6	6.7	94	6	8.0	3.41
15	7.0	6.8	6.6	6.7	94	6	7.2	3.42
16	7.0	6.8	6.7	6.8	94	7	7.7	3.41
17	7.0	6.9	6.8	6.8	94	7	7.7	3.52
18	7.0	6.9	6.9	6.9	94	9	7.8	3.56
19	7.1	7.0	7.0	7.0	94	7	8.7	3.60
Check	6.4	6.4	6.4	6.3	94	5	6.8	3.14

* Three plants only survived in culture 4, four plants in culture 5, and five plants in culture 6. After becoming established the plants in these cultures made good growth.

progress. During the latter half of the growth period, however, these plants appeared to grow more rapidly than did those in the cultures the soil extracts of which had lower hydrogen-ion concentrations.

To bring out more clearly the relation of the hydrogen-ion concentrations of the soil extracts to the dry weights of alfalfa tops and to their nitrogen content, the values representing these measurements taken from the proper columns of table 1, were plotted to form the graphs of figure 1, the broad,

narrow, and dotted lines representing, respectively, the dry weights of tops, average pH values, and per cent of nitrogen in the alfalfa tops. The single set of ordinates may here refer to dry weights, pH values, or percentages of nitrogen when applied to the graphs representing these measurements.

The graph representing dry weights, although it is somewhat irregular, shows a general agreement with the graph of pH values, in sloping gradually upward to the right. This indicates a gradual increase in the yields of alfalfa tops with corresponding decrease in the hydrogen-ion concentration of the soil extracts from the various cultures. It will be observed, however, that cultures 13 and 14, for which average hydrogen-ion exponents of 6.5 and 6.7 are indicated, produced almost as high yields as did culture 19, showing an

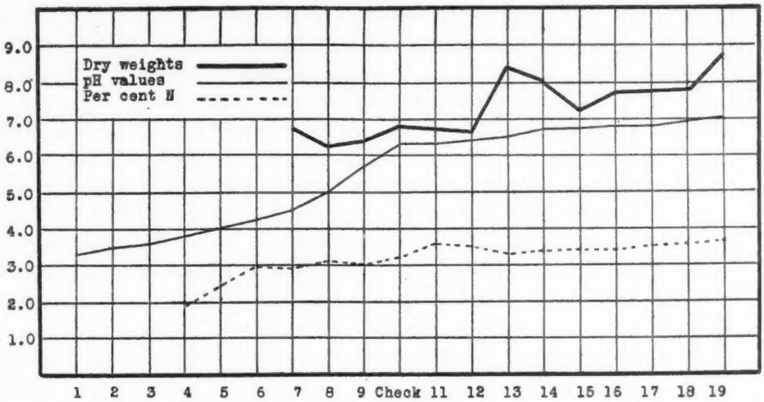

FIG. 1. GRAPHS SHOWING THE RELATION OF YIELDS AND PER CENT NITROGEN CONTENT OF ALFALFA TOPS TO THE REACTION OF THE SOIL IN WHICH THE PLANTS WERE GROWN

Ordinates represent grams, pH values, or percentages when referred to yields, soil reaction, or nitrogen content, respectively.

average hydrogen-ion exponent of 7.0. It is important here to note that the plants in the cultures with higher hydrogen-ion concentrations of the soil water, particularly in the cultures in which the soil reaction was adjusted by the use of sulfuric acid, showed better root development than did the plants in the cultures in which the soil water had a very low hydrogen-ion concentration or a neutral reaction. This is perhaps to be ascribed to the effect of the sulfates formed by the introduction of sulfuric acid into the soil. Hart and Tottingham (5) have shown that sulfates have an especially beneficial influence on root development, particularly on the roots of red clover, to which alfalfa bears a close relationship and may respond to the influence of sulfates in a similar manner.

A very interesting feature of the effect of soil reaction on the growth of alfalfa is its influence upon the nitrogen content of the plants. As the graphs of figure 1 clearly show, the nitrogen content of the plants increases correspondingly as the average hydrogen-ion exponents of the soil extracts from the different cultures increase. In a general way the same relation exists between the relative number of nodules formed on the roots of the plants in the various cultures and the hydrogen-ion exponents of the soil extracts, as may be observed from an examination of the data in table 1. Lipman and Blair (10) have pointed out that the nitrogen content of leguminous plants grown on unlimed plots is lower than is that of plants of the same species grown on limed plots. They correlate this phenomenon directly with the greater abundance of nodules on the roots of the plants grown on the limed plots, which indicates a greater capacity of the nodule-forming organisms for the fixation of atmospheric nitrogen, thus furnishing the plants with a greater supply of available nitrogen. This, however, does not explain the increased nitrogen content of non-leguminous plants grown on limed plots as compared with those grown on unlimed plots, a fact which was reported by these same authors in an earlier publication (9).

In this connection it might be suggested that the soil conditions which influence the activity of the nodule-forming organisms may in a like manner influence the nitrogen assimilation of non-leguminous as well as of leguminous plants. Whatever may be the true explanation, it appears that the reaction (hydrogen-ion concentration) of the medium in which the plants are grown has a direct influence upon the nitrogen content of the plants.

It is to be emphasized that no attempt was here made to determine the specific soil reaction as indicated by the hydrogen-ion exponents of the soil extracts to which the alfalfa plant responds best. To do this would necessitate extending the range of soil reactions to include hydrogen-ion exponent values considerably beyond the neutral point on the alkaline side. With the soil type here used this could not be accomplished without too greatly altering the proportions of the mineral constituents of the soil solution. It is, of course, quite probable that each soil type possesses a specific optimum or an optimum range of hydrogen-ion concentration values for the growth of alfalfa which is different from that of other soil types.

SUMMARY

Alfalfa was grown in pots containing soil the reaction of which was adjusted by the use of sulfuric acid and calcium carbonate. A series of 20 cultures was prepared showing a range in the hydrogen-ion concentrations of the soil extracts varying at somewhat irregular intervals from a pH value of 3.0 to one of 7.1. Water extracts of the soil from each culture were prepared at regular intervals during the growth of the plants and the hydrogen-ion concentrations determined by the colorimetric method.

1. The germination of alfalfa seeds was practically the same with pH values of the soil varying from 4.5 to 7.0, but was greatly reduced in cultures which yielded soil extracts having pH values below 4.5.

2. Yields of alfalfa tops showed a gradual increase with an increase in the pH values of the soil extracts from 3.8 to 7.0. The alfalfa plants experienced difficulty in becoming established in cultures yielding soil extracts with high hydrogen-ion concentrations, but after becoming established they showed normal green color, high vigor, and made excellent growth in soil having a pH value as low as 3.8.

3. With increasing hydrogen-ion concentration of the soil extracts, nodule formation on the roots of the plants was correspondingly less abundant.

4. Plants in the cultures which yielded soil extracts with very low hydrogen-ion concentrations showed poorer root development than did the plants in the cultures with higher hydrogen-ion concentrations of the soil extracts.

5. The nitrogen content of the plants showed a gradual increase with a corresponding decrease in the hydrogen-ion concentration of the soil extracts.

REFERENCES

(1) Clark, W. M., and Lubs, H. A. 1917 The colorimetric determination of hydrogen-ion concentration and its application in bacteriology. *In* Jour. Bact., v. 2, no. 1, p. 1–34; no. 2, p. 109–136; no. 3, p. 193–236.

(2) Gillespie, L. J. 1916 The reaction of soil and measurements of hydrogen-ion concentration. *In* Jour. Wash. Acad. Sci., v. 6, no. 1, p. 7–16.

(3) Gillespie, L. J. 1920 Colorimetric determination of hydrogen-ion concentration without buffer mixtures, with special reference to soils. *In* Soil Sci., v. 9, no. 2, p. 115–136.

(4) Gillespie, L. J., and Hurst, L. A. 1917 Hydrogen-ion concentration measurements of soils of two types; Caribou loam and Washburn loam. *In* Soil Sci., v. 4, no. 4, p. 313–319.

(5) Hart, E. B., and Tottingham, W. E. 1915 Relation of sulfur compounds to plant nutrition. *In* Jour. Agr. Res., v. 5, no. 6, p. 233–250.

(6) Hoagland, D. R. 1917 The effect of hydrogen and hydroxyl-ion concentration on the growth of barley seedlings. *In* Soil Sci., v. 3, no. 6, p. 547–560.

(7) Joffe, J. S. 1920 Hydrogen-ion concentration measurements of soils in connection with their "lime-requirements." *In* Soil Sci., v. 9, no. 4, p. 261–266.

(8) Knight, H. G. 1920 Acidity and acidimetry of soils. 2. Investigation of acid soils by means of the hydrogen electrode. *In* Jour. Indus. Engin. Chem., v. 12, no. 5, p. 457–464.

(9) Lipman, J. G., and Blair, A. W. 1915 Lime as a factor in the utilization of nitrogen. *In* N. J. Agr. Exp. Sta. 36th Ann. Rpt., p. 204.

(10) Lipman, J. G., and Blair, A. W. 1918 The influence of lime upon the yield of dry matter and nitrogen from different varieties of soybeans. *In* N. J. Agr. Exp. Sta. 39th Ann. Rpt., p. 190.

(11) Plummer, J. K. 1918 Studies in soil reaction as indicated by the hydrogen electrode. *In* Jour. Agr. Res., v. 12, no. 1, p. 19–31.

(12) Sharp, L. T., and Hoagland, D. R. 1916 Acidity and adsorption in soils as measured by the hydrogen electrode. *In* Jour. Agr. Res., v. 7, no. 3, p. 123–145.

(13) Wherry, E. T. 1916 A chemical study of the habitat of the walking fern, *Camptosorus rhizophyllus* (L) Link. *In* Jour. Wash. Acad. Sci., v. 6, no. 20, p. 672–679.

THE EFFECT OF FERTILIZERS ON BLUEBERRIES[1]

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In a recent paper (1) the writer has shown the effect of certain fertilizers upon the yield of cranberries, in the course of experimental work conducted at Browns Mills, N. J., in 1919. A large blueberry plantation situated on the same property as the cranberry substation gave the writer an exceptional opportunity to observe the effect of certain commercial fertilizers applied to the blueberry. The blueberry (*Vaccinium corymbosum*) is a close relative of the cranberry (*Vacinium oxycoccus*). The commercial cultivation of the former is practically new, although the latter has been grown under artificial conditions for a half-century. The soil on which both plants are grown has a slightly acid reaction, and is usually more or less sandy and well irrigated.

Many papers have been published on the commercial culture of the blueberry by F. V. Coville, of the Bureau of Plant Industry, United States Department of Agriculture (2, 3, 4, 5,).

The blueberry plantation at Browns Mills is 4 to 5 years old. Early in the spring of 1919 the plants started slowly with a starved yellow appearance, and the large set of fruit buds showed no probability of maturing fruit unaided. An application of plant-food suggested itself as a means of increasing the active leaf surface of the plant, thereby increasing the fruiting possibilities. The writer was asked to recommend a mixture which, in his opinion, would be the most economical. Because of lack of space for experiments, it was necessary to reduce the problem to a choice among three substances. Experience with the cranberry plant led the writer to believe that the question was whether a quick acting mineral fertilizer or a more slowly available mixture was best suited to the needs of the blueberry plant, and also how much the plant was in need of nitrogen. Basing the work on this judgment the writer planned an experiment of five plots, arranged and treated as in table 1.

The fertilizer applied on these plots was purposely put on in large amounts in order to get results which could be interpreted within the shortest possible time. At the end of 2 weeks a very great difference was noted in the plant growth. The proportion of leaf surface to fruit had increased in all the plots receiving plant-food. In plot 2 the leaves and new stems showed

[1] Paper No. 7 of the Technical Series, New Jersey Agricultural Experiment Stations, Cranberry Substation.

the dark green color peculiar to plots having an overdose of nitrogen. Plots 3 and 5 both showed more foliage than plot 4 and the general appearance of plot 5 seemed to be best. From these early indications the writer recommended an application of 600 pounds of a mixture similar to that on no. 5. Throughout the year plots 3 and 5 had an exceptionally good appearance, growing larger and having larger berries than plot 4.

TABLE 1

Fertilizer treatments per acre on blueberries

PLOT NUMBER	TREATMENT
1	Nothing
2	250 lbs. nitrate of soda
3	250 lbs. nitrate of soda 750 lbs. acid phosphate 250 lbs. Nebraska potash
4	Nothing
5	170 lbs. nitrate of soda (15.20 per cent N) 230 lbs. dried blood (13.2 per cent N) 340 lbs. steamed bone (2.50 per cent N; 22.90 per cent P_2O_5) 340 lbs. phosphate rock (26.90 per cent P_2O_5) 170 lbs. Nebraska potash (28.5 per cent K_2O)

The yield in 1919 was not recorded because of lack of help at the bearing season. However, it was noted that individual berries on the plots receiving the fertilizer were much larger than on the check plots.

In the spring of 1920 the blossoms on plots 2 and 3 were so numerous that it was evident again that the bushes could not mature all the fruit. This was especially evident on plot 3. The bushes in plot 5, while they seemed to have a preponderance of blossoms over leaves, were in much better condition than those on plot 3.

The applications made in 1919 were repeated in 1920, except that plot 5 was divided into two parts and only half of the plot received the treatment. This made 6 plots. The crop yields were taken on three rows, each a different strain of blueberry, and the yields of plots 5 and 6 were doubled in order to make their yield comparable to the yields of the other plots of twice their size.

The detailed crop record is given in table 2.

The plots show that the fertilizer treatment did not hurry the ripening of the berries in any great degree, as the rows matured quite evenly.

Table 3 presents the yields calculated on the acre basis.

The large yield of plot 1 over that of plot 4 is due to the fact that the plants in plot 1 are one year older than the plants in plot 4. Plots 5 and 6 have practically the same yield, or at least within the limits of experimental error.

This seems to indicate that the fertilizer applied last year is sufficient to last two years. The outstanding fact in the table, however, is that a well chosen fertilizer mixture increased the crop to a point three times as great as the yield of the nearest untreated plot.

TABLE 2

Yield of blueberries on experimental plots

	JULY 17	JULY 28	AUGUST 4	AUGUST 11	AUGUST 18	TOTAL
	qts.	*qts.*	*qts.*	*qts.*	*qts.*	*qts.*
Plot 1						
Row 1	2.00	2.30	1.00	0.50	None	5.80
Row 2	4.20	2.50	1.10	0.20	None	8.00
Row 3	5.00	5.00	1.40	0.20	None	11.60
To al						25.40
Plot 2						
Row 1	2.50	4.16	2.00	1.00	None	9.66
Row 2	2.80	2.65	0.90	0.15	None	6.50
Row 3	2.20	1.65	0.65	0.20	None	4.70
Total						20.86
Plot 3						
Row 1	3.00	2.00	2.15	2.15	2.00	9.30
Row 2	5.10	10.60	1.70	0.40	None	17.80
Row 3	6.30	1.90	1.30	0.30	None	9.80
Total						36.90
Plot 4						
Row 1	2.50	2.00	0.50	0.12	None	5.12
Row 2	2.70	2.30	0.90	0.10	None	6.00
Row 3	2.70	1.80	0.80	0.20	None	5.50
Total						16.62
Plot 5						
Row 1	5.50	11.00	4.50	3.00	1.50	25.50
Row 2	4.30	3.50	1.00	0.10	1.50	10.40
Row 3	8.00	5.00	1.60	0.20	None	14.80
Total						50.70
Plot 6						
Row 1	3.30	12.50	7.50	2.10	2.50	28.40
Row 2	3.50	4.00	1.00	0.10	None	8.60
Row 3	9.00	4.00	1.50	0.25	None	14.75
Total						51.75

The varieties represented in each row are: Row 1, Dunfee; row 2, Inman I; row 3, Inman II.

On August 10 the new growth started on all fertilized plots, in some cases being 8 inches long by August 18. This, of course, is of great advantage in setting buds for next year's crop. On August 21 none of the check plots had started new vine growth.

TABLE 3

Acre yields of blueberries on experimental plots

PLOT NUMBER	TREATMENT, 1919	TREATMENT, 1920	YIELD, 1920
			qts.
1	Nothing	Nothing	1016.0
2	250 lbs. nitrate of soda	Same as in 1919	834.4
3	250 lbs. nitrate of soda 750 lbs. acid phosphate 250 lbs. Nebraska potash	Same as in 1919	1476.0
4	Nothing	Nothing	664.8
5	170 lbs. nitrate of soda 230 lbs. dried blood 340 lbs. steamed bone 340 lbs. phosphate rock 170 lbs. Nebraska potash	Same as in 1919	2028.0
6	Same as plot 5	Nothing	2070.0

REFERENCES

(1) Beckwith, Charles S. 1919 The effect of certain nitrogenous and phosphatic fertilizers on the yield of cranberries. *In* Soil Sci., v. 8, no. 6, p. 483–490.

(2) Coville, Frederick V. 1916 Directions for blueberry culture. U. S. Dept. Agr. Bul. 334.

(3) Coville, Frederick V. 1902 Blueberries. *In* Bailey's Encyclopedia of Horticulture, v. 4, p. 1889.

(4) Coville, Frederick V. 1911 Taming the wild blueberry. *In* Nat. Geogr. Mag., v. 22, p. 137–147.

(5) Coville, Frederick V. 1916 The wild blueberry tamed. *In* Nat. Geogr. Mag., v. 29, p. 535–546.

PLATE I

Fig. 1. Typical bush on plot 4, untreated.

Fig. 2. Typical bush on plot 6, treated with fertilizer in 1919.

EFFECT OF FERTILIZERS ON BLUEBERRIES

CHARLES S. BECKWITH

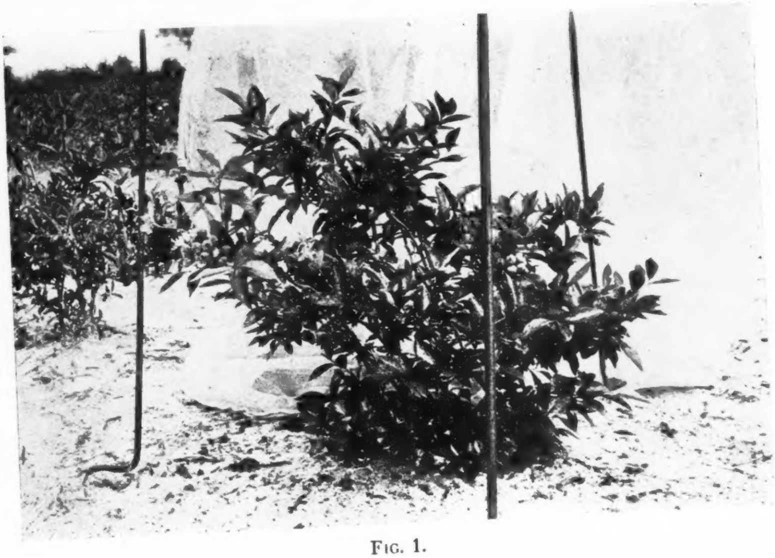

FIG. 1.

FIG. 2.

COÖPERATIVE EXPERIMENTS FOR THE COMPOSTING OF PHOSPHATE ROCK AND SULFUR

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In Virginia the limiting factor in plant production is more often phosphorus than any of the other plant-food elements. This is proven by the widespread use of acid phosphate by the farmers of Virginia as well as by experiments conducted by the Experiment Station in different localities. Increased yields are nearly always obtained when acid phosphate is used as the carrier of phosphorus. There are other carriers of phosphorus available for use, and the relative merit of these different phosphates for agricultural purposes has been under investigation for a long time. When acid phosphate and rock phosphate have been compared, the results show that the ground rock phosphate is very slowly available and that it rarely increases the yield, at least on Virginia soils (4).

Rock phosphate, the chief source of all phosphorus fertilizers, occurs in vast deposits and it may be used with no other preparation than grinding, but the bulk of it is treated with an equal amount of sulfuric acid and converted into acid phosphate. Although this contains only about half as much phosphorus as the original rock, it is considered a much better fertilizer because the plant-food is immediately available.

A series of investigations conducted in this country and in Europe suggested to Lipman that sulfur, when composted with phosphate rock and soil, would increase the availability of the phosphorus. Lipman, McLean and Lint (5), Brown and Gwinn (2), and Ames and Richmond (1), have made investigations and have demonstrated that available phosphoric acid is produced by such treatment. For a complete bibliography see the article by McLean on the oxidation of sulfur by microörganisms (6).

In 1917 the demand for sulfuric acid for the manufacture of munitions became so great that it was feared that the supply for the manufacture of acid phosphate would be curtailed or even cut off entirely. This shortage of acid increased the cost of acid phosphate and at the same time the demand for increased crops became imperative.

In November, 1917, the National Research Council, Council of National Defense, called a meeting of agricultural workers to consider means of increasing the availability of the phosphorus in rock phosphate, which could be used as a substitute for acid phosphate. The results recorded in this paper were obtained by conducting experiments outlined at this meeting.

The primary object of the experiment was to determine the changes that would take place when phosphate rock was composted with soil, sulfur and manure.

Materials used

Phosphate rock. The floats used was a commercial sample sold by Armour and Company of Chicago, which contained 30.99 per cent P_2O_5; apparently it was a blue rock phosphate from Tennessee.

Sulfur. Commercial ground sulfur was used.

Manure. The manure used was a mixture of horse manure and cut straw. The manure contained 76 per cent water and 0.4 per cent nitrogen.

Soil. The soil employed was obtained from the Virginia Experiment Station's plats and belonged to the Hagerstown series. It was a clay loam and had never been limed. Its composition is given in table 1.

TABLE 1

Analysis of limestone clay loam (air-dried), surface soil

	per cent
Insoluble matter (in hydrochloric acid, sp. gr. 1.115)	89.56
Potash	0.16
Soda	0.09
Lime	0.76
Magnesia	0.71
Iron oxide	0.87
Alumina	1.47
Phosphoric acid	0.07
Sulfuric acid	0.03
Water and organic matter	4.36
Humus	0.81
Nitrogen	0.136
Total potash (by J. Lawrence Smith method)	0.200
Total phosphoric acid (by fusion method)	0.133
So-called available potash (by 0.2 *N* nitric acid method)	0.020370
So-called available phosphoric acid (by 0.2 *N* nitric acid method)	0.004070

Water. Water used in keeping up the moisture content of the composts was tap water and contained 0.0014 per cent SO_3 in combination with calcium as calcium sulfate.

Composts. The composts were made up on a concrete floor. The inoculated soil, furnished by the New Jersey Agricultural Experiment Station, was first mixed with about 20 pounds of soil and was then thoroughly incorporated with 50 pounds of soil, and finally mixed with the whole portion. The sulfur was mixed thoroughly with the phosphate rock and finally the entire amount of phosphate rock, sulfur and soil was thoroughly mixed with a shovel.

A small quantity of each mixture was withdrawn and the water-holding capacity of each heap was determined. Then sufficient water was added to bring the moisture content of each heap to about 60 per cent saturation.

The composts remained on a concrete floor under glass for the first 12 months, then all the composts were put in large boxes. Each compost was stirred thoroughly every 10 days. In order to hold the water content between 50 and 60 per cent of its water-holding capacity, it was necessary to cover the heaps with sacking to prevent the too rapid loss of water by evaporation. The temperature was taken at least once a day and generally twice, throughout the first year. Apparently the temperature varied directly with the day. None of the heaps showed any evidence of heating up. After the first year the water content was not kept within such narrow limits, the piles being allowed to dry to a considerable extent before the moisture content was brought back to 60 per cent of the water-holding capacity.

Samples were taken from composts 1A and 1B (table 2) about the first of each month. Those from 2A and 2B were taken on the fifteenth, as the second set of composts were started 15 days later than the first.

TABLE 2

Composition of composts

	NO. 1A	NO. 1B	NO. 2A	NO. 2B
	lbs.	*lbs.*	*lbs.*	*lbs.*
Soil	200*	400	200*	400
Ground rock phosphate	600	600	600	600
Manure			200	200
Sulfur	200		200	

* Included the inoculated soil.

EXPERIMENTAL WORK

In carrying out this work it was necessary to determine water-soluble phosphoric acid, ammonium-citrate-soluble phosphoric acid, total phosphoric acid, and the sulfur present as sulfate. The following methods were used:

Water-soluble phosphoric acid. Ten grams of the sample were weighed out, put on a small filter and washed with hot water until the filtrate measured 500 cc. An aliquot was analyzed by gravimetric or volumetric methods.

Ammonium-citrate-soluble phosphoric acid. The method followed was suggested by J. W. Ames, and was practically the same as used by Shedd (6). Ten grams of material were treated with 100 cc. neutral ammonium-citrate solution and made up to 500 cc., and an aliquot of the filtrate was taken for analysis.

Total phosphoric acid. Aqua regia or sulfuric acid was used as the solvent.

Sulfuric acid. Two grams were taken and made up to 100 cc. with 1 per cent hydrochloric acid; this was shaken once every hour through the day, allowed to stand over-night, filtered and an aliquot taken for analysis.

Where the sulfur was used in the compost, the manure had not disintegrated at the end of two years.

In composts 1A and 2A both the water-soluble and ammonium-citrate-soluble phosphoric acid gradually increased (table 3). In 1A the compost of soil, ground rock phosphate and sulfur, the water-soluble phosphate increased from 0.02 per cent to 0.88 per cent, and the ammonium-citrate-soluble from 0.32 per cent to 3.10 per cent. Where manure and sulfur were used in the compost the water-soluble phosphate increased from 0.02 per cent to 1.06 per cent, and the ammonium-citrate-soluble from 0.39 to 3.35 per cent. In

TABLE 3

Water-soluble and ammonium-citrate-soluble phosphoric acid (P_2O_5) found in the composts

DATE OF TAKING SAMPLE	NO. 1A. SOIL, GROUND ROCK PHOSPHATE AND SULFUR		NO. 1B. SOIL AND GROUND ROCK PHOSPHATE		NO. 2A. SOIL, MANURE, GROUND ROCK, PHOSPHATE AND SULFUR		NO. 2B. SOIL, MANURE, GROUND ROCK PHOSPHATE	
	Water-soluble	Ammonium-citrate-soluble	Water-soluble	Ammonium-citrate-soluble	Water-soluble	Ammonium-citrate-soluble	Water-soluble	Ammonium-citrate-soluble
1918	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
January	0.02	0.32	Trace	0.30	0.02	0.39	Trace	0.39
February	0.03	0.35	Trace	0.30	0.02	0.38	Trace	0.39
March	0.03	0.36	Trace	0.31	0.02	0.36	Trace	0.37
April	0.10	0.37	Trace	0.34	0.40	0.96	Trace	0.38
May	0.30	1.06	Trace	0.29	0.56	1.37	Trace	0.35
June	0.70	1.45	Trace	0.30	0.90	1.88	Trace	0.36
July	0.78	1.63	Trace	0.30	0.80	2.18	Trace	0.32
August	0.77	1.88	Trace	0.30	0.77	2.28	Trace	0.31
September	0.78	2.00	Trace	0.32	0.82	2.45	Trace	0.31
October	0.79	2.30	Trace	0.34	0.83	2.85	Trace	0.32
November	0.80	2.42	Trace	0.32	0.90	2.81	Trace	0.37
December	0.77	2.45	Trace	0.32	0.92	2.87	Trace	0.31
1919								
January	0.82	2.42	Trace	0.30	0.87	2.75	Trace	0.33
March	0.54	2.42	Trace		0.66	2.64	Trace	
June	0.76	2.62	Trace	0.57	0.91	3.06	Trace	0.45
September	0.77	2.79	Trace	0.60	1.06	3.35	Trace	0.33
1920								
January	0.88	3.01	0.02	0.67	0.56	3.12	0.02	0.31

this instance the maximum percentage occurred in September, 1919, and dropped at the next analysis in January.

In 1B and 2B both the water-soluble and ammonium-citrate-soluble phosphoric acid remained practically constant throughout the whole experiment. In 1B, the compost without manure, the ammonium-citrate-soluble phosphoric acid increased 0.37 per cent in the last two determinations.

The increase in the percentage of sulfur as SO_3 goes hand in hand with the increase of available phosphorus, and in fact slightly precedes the gain of the latter, as shown in table 4.

TABLE 4

Sulfur present as SO_3

DATE OF TAKING SAMPLE	NO. 1A. SOIL, GROUND ROCK PHOSPHATE AND SULFUR	NO. 1B. SOIL AND GROUND ROCK PHOSPHATE	NO. 2A. SOIL, MANURE, GROUND ROCK PHOSPHATE AND SULFUR	NO. 2B. SOIL, MANURE AND GROUND ROCK PHOSPHATE
1918	*per cent*	*per cent*	*per cent*	*per cent*
January	1.11	1.01	1.10	1.11
February	1.05	1.03	1.09	1.16
March	1.62	0.96	2.45	1.06
April	2.43	0.99	2.94	1.11
May	3.32	1.14	3.40	1.11
June	4.17	1.24	3.78	1.52
July	4.36	1.01	6.20	1.43
August	7.12	1.50	6.35	1.70
September	7.81	1.45	8.00	1.70
October	8.46	1.40	8.52	1.53
November	8.75	1.40	6.52	1.52
December	7.13	2.20	6.61	1.51
1919				
January	7.73	2.37	7.13	1.38
March	8.40		8.16	
June	9.04	3.06	8.66	1.68
September	9.21	3.50	8.15	1.98
1920				
January	8.92	3.57	7.70	1.92

TABLE 5

Comparison of the availability of phosphoric acid

	NO. 1A	NO. 1B	NO. 2A	NO. 2B
	per cent	*per cent*	*per cent*	*per cent*
At the beginning:				
Total P_2O_5	19.13	18.81	18.33	18.11
Water-soluble P_2O_5	0.02		0.02	
Ammonium-citrate-soluble P_2O_5	0.32	0.30	0.39	0.39
Total P_2O_5 available	1.67	1.59	2.13	2.15
December, 1919 (end 1 year):				
Total P_2O_5	16.35	18.81	15.52	18.81
Water-soluble P_2O_5	0.77		0.92	
Ammonium-citrate-soluble P_2O_5	2.45	0.32	2.87	0.31
Total P_2O_5 available	14.98	1.70	18.48	1.64
January 8, 1920 (end second year)				
Total P_2O_5	16.30	18.44	16.16	18.36
Water-soluble P_2O_5	0.88	0.02	1.06	
Ammonium-citrate-soluble P_2O_5	3.01	0.67	3.35	0.33
Total P_2O_5 available	18.47	3.63	20.73	1.80

The greatest increase in sulfate was found where soil, sulfur and rock phosphate were composted. The amount was greater than in compost 2A, where manure was present. At the beginning, the addition of manure apparently increased the sulfate formation, but by the end of the year the compost without the manure contained the higher percentage of sulfates.

Where soil and ground rock phosphate were composted the percentage of sulfates remained more or less constant for a year, and then a slight increase occurred. The increase was from 1.01 per cent to 3.57 per cent. Where manure was added the percentage of sulfates did not increase very much the first year and the total increase was not as great as that in compost 1B.

In compost 2A where sulfur, manure, soil and rock phosphate were used, the available phosphoric acid increased from 2.13 per cent to 20.73 per cent (table 5). The next largest increase was shown in compost 1A which contained phosphate rock, soil and sulfur. The available phosphoric acid increased from 1.67 to 18.47 per cent.

In the composts where no sulfur was added, there was practically no increase of available phosphoric acid, and in compost 2B where manure was added, there was a loss of available phosphoric acid.

Supplementary Experiment No. 1. A supplementary experiment was undertaken which had for its object the study of the changes that would occur in the nitrogen content of manure, where sulfur and rock phosphate were used as preservatives. The composts were prepared and analyzed substantially as those discussed above, and had the following composition:

	COMPOST A	COMPOST B
	lbs.	*lbs.*
Manure	500	500
Floats	5	5
Sulfur	$1\frac{2}{3}$	

During the first year these composts were stirred thoroughly once every 10 days and watered whenever the moisture content was low. Samples were taken about the fifteenth of the month, air-dried, ground and analyzed. The ammonia, nitrate and total nitrogen content of the compost were determined in the original samples and at intervals running over a period of two years.

The results given in table 6 show that the percentage of total nitrogen in compost A remained practically constant. In compost B, where sulfur was absent, the nitrogen percentage showed an increase due to the decomposition of the organic matter.

The nitrate content of compost A remained constant, the ammonia content increased from 0.015 per cent to as high as 0.424 per cent of nitrogen, gradually increasing for six months and then gradually dropping until at the end of two years, when only 0.098 per cent of nitrogen was present.

In compost B the nitrogen as nitrates increased from 0.045 to 0.526 per cent, the high mark being reached at the end of one year. At the end of

TABLE 6

Nitrogen content of dry samples

DATE	TOTAL NITROGEN		NITROGEN AS NITRATES		NITROGEN AS AMMONIA	
	A	B	A	B	A	B
1918	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Sample No. 1	1.657	1.756	0.067	0.045	0.015	0.030
February	1.812	1.980	0.038	0.068	0.091	0.015
April 14	1.904	2.395	0.007	0.076	0.202	0.015
May 15	1.825	2.425	0.045	0.407	0.328	0.030
June 17	1.968	2.370	0.045	0.414	0.415	0.030
July 15	1.713	2.393	0.000	0.498	0.424	0.045
August 15	1.814	2.366	0.030	0.487	0.404	0.045
September 16	1.803	2.332	0.000	0.501	0.327	0.030
October 15	1.745	2.479	0.030	0.487	0.304	0.015
November 15	1.632	2.329	0.052	0.473	0.224	0.030
December 11	1.758	2.355	0.067	0.526	0.252	0.015
1919						
January 11	1.685	2.441	0.045	0.442	0.260	0.015
June 2	1.547	2.341	0.112	0.416	0.142	0.015
September 2	1.577	2.287	0.044	0.476	0.118	0.022
1920						
January 8	1.609	2.190	0.053	0.391	0.098	0.008

A = Manure, floats and sulfur; B = manure and floats.

TABLE 7

Comparison of nitrogen determinations

	A. MANURE, ROCK PHOSPHATE AND SULFUR		B. MANURE AND ROCK PHOSPHATE	
	February, 1918 beginning	January, 1920 end	February, 1918 beginning	January, 1920 end
Weight of mixture	506⅔ lbs.	200 lbs.	505 lbs.	109 lbs.
Per cent of water	76.46	66.48	77.03	55.09
Amount of dry matter	119.27 lbs.	67.04 lbs.	116.00 lbs.	48.95 lbs.
Per cent of nitrogen	0.398	0.5388	0.410	0.9844
Total amount of nitrogen	2.012 lbs.	1.0776 lbs.	2.072 lbs.	1.073 lbs.
Dry matter lost	52.23 lbs., or 43.79 per cent		67.05 lbs. or 57.80 per cent	
Nitrogen lost	0.934 lbs., or 46.66 per cent		0.999 lbs. or 48.21 per cent	
Amount of nitrogen as ammonia	0.047 lbs. gain		0.031 lbs. loss	
Amount of nitrogen as nitrate	0.046 lbs. loss		0.148 lbs. gain	

two years the nitrate content had dropped to 0.391 per cent of nitrogen. The ammoniacal nitrogen remained practically constant.

Compost A, where sulfur was present, did not lose as much organic matter by the various decomposing agents as compost B. The difference in weight

TABLE 8

Sulfofying power of certain Virginia soils

SOIL	SULFUR AS SO_4 MAY 2	SULFUR AS SO_4 MAY 11	SULFUR AS SO_4	AMOUNT OF SULFUR ADDED	SULFUR OXIDIZED
Loudon County	*mgm.*	*mgm.*	*mgm.*	*mgm.*	*per cent*
Penn gravelly loam	0.42	7.04	6.62	13.33	49.66
Penn stony loam	1.27	1.39	0.12	13.33	0.90
Penn loam	2.78	4.79	2.01	13.33	15.08
Cecil mica loam	0.87	3.63	2.76	13.33	20.71
Penn clay	1.11	3.92	2.81	13.33	21.08
Cecil clay	3.75	4.60	0.85	13.33	6.38
Cecil loam	2.22	4.74	2.52	13.33	18.90
Cecil silt loam	1.67	6.36	4.69	13.33	35.18
Iridell clay loam	1.39	5.16	3.77	13.33	28.28
Loudon sandy loam	1.67	6.36	4.69	13.33	35.18
Frankstown gravelly loam	0.73	4.95	4.22	13.33	31.66
Fredericksburg stony loam	1.51	4.17	4.66	13.33	19.95
Fredericksburg silt loam	1.67	10.32	8.65	13.33	64.89
DeKalb silt loam	3.95	6.06	2.11	13.33	15.83
DeKalb gravelly loam	2.36	3.43	1.07	13.33	8.03
Hagerstown stony clay loam	3.33	7.04	3.71	13.33	27.83
Hagerstown clay loam	2.22	4.44	2.22	13.33	16.65
Berks shale loam	2.22	4.76	2.54	13.33	19.05
Berks silt loam	2.22	4.94	2.72	13.33	20.41
Bedford County					
Murrill clay loam	0.86	2.16	1.30	13.33	9.75
Murrill fine sandy loam	0.81	2.25	1.44	13.33	10.80
Campbell county					
Iridell fine sandy loam	0.69	2.22	1.53	13.33	11.48
Louisa fine sandy loam	0.50	2.68	2.18	13.33	16.35
York loam	0.88	2.22	1.34	13.33	10.05
York free sandy loam	0.73	2.25	1.52	13.33	11.40
Louisa loam	0.75	2.22	1.47	13.33	11.03
Appomattox County					
Cecil sandy loam	0.72	2.00	1.28	13.33	9.60
Cecil loam	1.75	2.36	0.61	13.33	4.58
Iridell clay loam	1.11	2.42	1.31	13.33	9.83
Cecil clay	0.91	2.50	1.59	13.33	11.93
Prince Edward County					
Worsham sandy loam	0.85	2.36	1.51	13.33	11.33
Durham sandy loam	0.81	2.11	1.30	13.33	9.75
Iridell clay loam	0.70	1.75	1.05	13.33	7.88
Norfolk County					
Leonardstown loam	0.82	2.22	1.40	13.33	10.50
James City County					
Leonardstown loam	0.83	1.75	0.92	13.33	6.90
Norfolk fine sandy loam	0.65	2.36	1.71	13.33	12.83
Albemarle County					
Cecil sandy loam	0.77	2.61	1.84	13.33	13.80
Cecil loam	0.73	2.22	1.49	13.33	11.18
Cecil clay	0.72	1.83	1.11	13.33	8.33

of the compost as well as the total amount of nitrogen present at the end of the experiment proved this. When the bacteria were counted, compost B, without sulfur, showed the presence of from three to four times as many bacteria as compost A.

When manure and ground rock phosphate were composted the nitrogen lost amounted to 48.21 per cent (table 7). The loss of nitrogen as ammonia was 0.031 pound, while there was a gain of 0.138 pound of nitrogen as nitrate. Where sulfur was used in the compost a gain of 0.047 pound of ammoniacal nitrogen was shown. The loss of nitrate nitrogen in composting was 0.046 pound. No increase of available phosphoric acid was found in either of the composts.

THE SULFOFYING POWER OF CERTAIN TYPES OF VIRGINIA SOIL

Table 8 gives the sulfofying power of some of the soil types of Virginia. The determinations are made by Mr. T. J. Murray, who followed Brown's (3) method. Sodium sulfate was the salt oxidized.

DISCUSSION

In compost 1A, which contained sulfur, soil and rock phosphate, 10.89 per cent of the total phosphoric acid was available after 7 months, 14.98 per cent after 12 months, and 18.47 per cent after 2 years.

In compost 2A, which contained manure, sulfur, soil and phosphate rock, a larger percentage of the total phosphoric acid was made available than in compost 1A without manure. At the end of 7 months 14.69 per cent was available, at the end of one year 18.48 per cent, and after 2 years 19.31 per cent.

Our results agree with those obtained by Brown and Gwinn (2) which show that more available phosphoric acid is produced where manure is included in the compost.

Shedd's results (7) with soil, rock phosphate and sulfur, in the same proportions used by us, agree fairly well for the first 7 months of the experiment, but where he used sulfur, soil, rock phosphate and manure in different proportions, there is a lack of agreement. Our results do not show as great sulfur oxidation with the accompanying high percentage of available phosphoric acid.

In composts 1A and 2A, over 10 per cent of the phosphoric acid was made available in 7 months. Where no sulfur was used in composts 1B and 2B, the available phosphoric acid remained practically constant throughout the experiment. There was a slight increase in the available phosphoric acid at the end of 2 years in compost 1B which contained soil and rock phosphate.

Manure did not increase the available phosphoric acid in compost 2B after 2 years, and the analyses showed less available phosphoric acid at the end of the experiment than was present at the beginning.

SUPPLEMENTARY EXPERIMENT NO. 1

Where 5 pounds of rock phosphate was added to 500 pounds of manure, 57.80 per cent of the dry matter and 48.21 per cent of nitrogen were lost in 2 years.

Where 5 pounds of rock phosphate, and 1⅝ pounds of sulfur were added to 500 pounds of manure, the decomposition was less. The losses were as follows: dry matter 43.79 per cent; nitrogen 46.44 per cent.

In compost A, with sulfur, ammoniacal nitrogen was produced whereas we do not find an increase of nitrates.

In compost B, without sulfur, nitric nitrogen was produced. There was a decrease in the ammoniacal nitrogen.

SUMMARY

1. The addition of sulfur to a compost of soil and rock phosphate increased the availability of phosphoric acid, but not to the same extent as when manure was added to a compost of soil, rock phosphate and sulfur.

2. In compost 1B and 2B, without sulfur, neither compost showed any appreciable increase in the availability of the phosphoric acid.

3. Sulfur oxidation preceded the increase of available phosphoric acid.

4. The addition of phosphate to manure slowed up the fermentation and there was a loss of only 57.80 per cent of dry matter and 48.21 per cent of nitrogen in 2 years. At the same time there is an increase of 0.138 pound of nitrate nitrogen and a loss of 0.031 pound of ammoniacal nitrogen.

5. The addition of sulfur and phosphate to manure checked the fermentation to a greater extent than the phosphate alone. There was a loss of only 43.77 per cent of dry matter and 46.44 per cent of nitrogen in 2 years. But here the increase in ammoniacal nitrogen was balanced by the loss in the nitrate nitrogen.

6. Upon the addition of rock phosphate to manure a large quantity of nitric nitrogen was formed. When sulfur also was added there was no nitrate formation but the ammonia content was greatly increased.

7. All of the Virginia soils tested had some sulfofying power, but there was a very great variation among the different soils.

8. The majority of the Virginia soils oxidized less sulfur than the soils tested by Shedd (7) of Kentucky and Brown and Kellogg (3) of Iowa.

9. The results of composting soil, sulfur, ground phosphate rock and manure, under the conditions suggested by the plan as outlined, do not in our opinion warrant the farmers of Virginia conducting experiments along similar lines, because the formation of available phosphoric acid is too slow to meet their needs. Besides, the farmer cannot be expected to keep the water-holding capacity of his composts up to the desired amount, and he is not likely to spade the composts every 10 or more days so that the proper oxidation would occur. Probably some conditions might arise or different propor-

tions of soil, rock phosphate, and sulfur be suggested, or a better starter or inoculating material might be used, which would give higher sulfur oxidation and thereby produce more available phosphoric acid than is possible under the conditions as outlined in this experiment.

REFERENCES

(1) Ames, J. W., and Richmond, T. E. 1918 Sulfocation in relation to nitrogen transformations. *In* Soil Sci., v. 5, no. 4, p. 311–321.

(2) Brown, P. E., and Gwinn, A. R. 1917 Effect of sulfur and manure on availability of rock phosphate in soil. Iowa Agr. Exp. Sta. Res. Bul. 43.

(3) Brown, P. E., and Kellogg, E. H. 1914 Sulfofication in soils. Iowa Agr. Exp. Sta. Res. Bul. 18.

(4) Ellett, W. B., and Ingham, A. A. 1917 Pot experiments to determine primarily the availability of phosphoric acid in Thomas slag phosphates in comparison with other phosphates. Va. Agr. Exp. Sta. Tech. Bul. 16.

(5) Lipman, Jacob G., McLean, Harry C., and Lint, H. C. 1916 Sulfur oxidation in soils and its effect on the availability of mineral phosphates. *In* Soil Sci., v. 6, no. 4, p. 499–538.

(6) McLean, Harry C. 1918 The oxidation of sulfur by microorganisms in its relation to the availability of phosphates. *In* Soil Sci., v. 5, no. 4, p. 251–290.

(7) Shedd, O. M. 1919 Effect of oxidation of sulfur in soils on the availability of rock phosphate and on nitrification. *In* Jour. Agr. Res., v. 18, no. 6, p. 329–345.

THE INFLUENCE OF INITIAL REACTION ON THE OXIDATION OF SULFUR AND THE FORMATION OF AVAILABLE PHOSPHATES[1]

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Earlier experiments on the production of soluble phosphates through the oxidation of sulfur have indicated certain more or less well defined steps both in the oxidation of the sulfur and in the formation of soluble phosphates. It would seem that the activities of the sulfur-oxidizing bacteria gain in intensity when the reaction of the medium becomes acid beyond a certain point. For this reason it has seemed advisable to determine whether by adjusting the reaction of the medium the processes of sulfur oxidation might be expedited. Accordingly, mixtures were made up of greenhouse soil, ground phosphate rock and flowers of sulfur. The proportions used were:

	grams
Soil	100
Tennessee rock phosphate, containing 31.12 per cent of total phosphoric acid	15
Flowers of sulfur	5

The mixtures were kept in tumblers with a moisture content of about 38 per cent. As shown in table 1, additions were made to the mixtures of different amounts of 0.1 *N* sulfuric acid. The largest amount of acid added to any of the tumblers was 45 cc. and the smallest 12 cc. No acid was added to the mixture used as a check.

When the experiment was begun on March 16, 1920, the initial hydrogen-ion exponent, the pH of Sörensen, ranged from 5.4 in mixture 16 to 4.7 in no. 15. In order to provide suitable inoculation there was added to each mixture 5 cc. of infusion prepared by shaking 100 gm. of material from an old sulfur-phosphate compost with 500 cc. of distilled water. It may be noted, in this connection, that these composts were originally made up in the fall of 1916 and that by the spring of 1920 the hydrogen-ion exponent as expressed in pH values was 1.6. Water extract for the determination of the hydrogen-ion concentration was prepared according to the method of Gillespie (2). The hydrogen-ion concentrations of the extract were determined by the colorimetric method, using the sulfonephthalein series of indicators as recommended by Clark and Lubs (1).

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Aside from the hydrogen-ion concentration determinations made from time to time, tests were made also for sulfates as a check on the amount of sulfuric acid produced. The soluble phosphates were determined by the method of the Official Agricultural Chemists. During the progress of the experiment the tumblers containing the different mixtures were kept covered with petri dishes. The weight of each tumbler and contents were marked on the petri dishes and the optimum amount of moisture was maintained by restoring the water lost by evaporation. Proper allowance was made for the small quantities of material withdrawn for the different determinations.

The progress of sulfur oxidation can be readily traced from the data given in table 2.

TABLE 1

Treatment of soil samples studied

MIXTURE NUMBER	pH	0.1 N H_2SO_4	H_2O
		cc.	*cc.*
1	5.0	12.0	29.0
2	5.0	14.4	26.6
3	5.1	16.8	24.2
4	5.1	19.2	21.8
5	5.0	21.4	19.6
6	5.0	24.0	17.0
7	5.0	26.4	14.6
8	5.0	28.8	12.2
9	5.0	31.2	9.8
10	5.0	33.6	7.4
11	4.8	36.0	5.0
12	4.9	38.4	2.6
13	4.8	40.8	0.2
14	4.9	43.2	0.0
15	4.7	45.0	0.0
16	5.4	0.0	41.0

It is quite evident from the data recorded in the table that the initial reaction did not appreciably affect the rate of sulfur oxidation, nor the rate of the formation of soluble phosphates. Within one week after the beginning of the experiment the pH was as low as 3.6 in mixture 13. At the end of the third week the pH was below 3.0 in all of the mixtures. It may be of interest to point out in this connection that in mixture 13 there was no calcium phosphate added and that, for this reason, there was a greater accumulation of acidity in the material than in any of the other mixtures where the calcium of the tricalcic phosphate served in part to neutralize the free sulfuric acid. At the end of the twelfth week the pH was below 2.0 in tumblers 6, 8 and 12, as well as in tumbler 13. Beyond that the increase in acidity was relatively slight.

It will be observed that the formation of available phosphate showed a very marked increase between the end of the second and the end of the third

TABLE 2

Sulfur oxidation as indicated by the availability of phosphate

NUMBER OF CULTURE	END OF FIRST WEEK		END OF SECOND WEEK		END OF THIRD WEEK		END OF FOURTH WEEK		END OF FIFTH WEEK		END OF SIXTH WEEK		END OF EIGHTH WEEK	
	pH	Available P	pH	Available P	pH	Available P	pH	Available P	pH	Available P	pH	Available P	pH	Available P
		per cent		*per cent*		*per cent*		*per cent*		*per cent*		*per cent*		*per cent*
1	4.2	3.75	3.0	4.25	2.8	13.26	2.8	14.72	2.6	15.3	2.4	23.2	2.6	31.8
2	4.1	3.90	3.0	4.25	2.8	14.84	2.8	15.40	2.6	17.1	2.4	26.2	2.4	32.7
3	4.1	4.01	3.0	5.00	2.8	15.02	2.8	15.50	2.4	19.1	2.4	28.4	2.4	33.7
4	4.1	4.01	3.0	6.78	2.8	11.46	2.8	13.30	2.6	18.7	2.4	27.9	2.6	35.2
5	4.0	4.21	3.0	6.76	2.8	12.52	2.8	13.30	2.4	19.4	2.3	30.0	2.4	36.3
6	4.0	4.21	3.0	7.80	2.8	15.94	2.8	15.60	2.4		2.4	26.8	2.2	31.4
7	4.1		3.0	7.80	2.8	14.72	2.8	15.40	2.4	19.5	2.4	26.3	2.4	32.0
8	4.1	4.60	3.0	7.80	2.8	17.64	2.8	17.30	2.4	19.4	2.4	27.0	2.2	32.6
9	4.0	5.23	3.0	7.55	2.8	15.40	2.8	15.60	2.4	19.3	2.4	27.2	2.2	33.2
10	4.0	4.60	3.4	4.74	2.8	17.60	2.8	19.14	2.4	21.3	2.3	30.6	2.2	36.7
11	4.1	4.01	3.6	4.60	2.8	14.64	2.8	14.64	2.6	15.3	2.4	24.2	2.4	32.9
12	4.1	4.50	3.0	4.90	2.8	15.64	2.8	16.56	2.4	20.4	2.4	27.3	2.1	34.2
13	3.6		3.4		2.4		2.4		2.4		2.0		2.0	
14	4.0	5.23	3.8	5.20	2.8	15.02	3.0	15.44	2.8	21.1	2.6	29.0	2.4	35.6
15	4.0	5.30	3.2	4.47	2.8	15.10	3.0	15.02	2.6	15.4	2.6	26.8	2.6	31.6
16	4.4	3.75	3.0	4.38	2.8	14.90	2.8	15.44	2.6	19.1	2.4	27.2	2.6	33.4

NUMBER OF CULTURE	END OF NINTH WEEK		END OF TENTH WEEK		END OF TWELFTH WEEK		END OF FOURTEENTH WEEK		END OF SIXTEENTH WEEK		END OF EIGHTEENTH WEEK		END OF TWENTIETH WEEK	
	pH	Available P	pH	Available P	pH	Available P	pH	Available P	pH	Available P	pH	Available P	pH	Available P
		per cent		*per cent*		*per cent*		*per cent*		*per cent*		*per cent*		*per cent*
1	2.4	35.2	2.3	42.4	2.2	59.8	2.2	59.0	2.2	66.9	2.1	76.3	1.9	83.6
2	2.4	36.1	2.3	43.0	2.2	59.6	2.2	60.1	2.2	68.4	2.1	77.2	2.0	83.9
3	2.4	36.2	2.3	44.1	2.2	60.1	2.3	59.4	2.3	64.6	2.2	73.5	2.0	84.9
4	2.6	36.4	2.2	45.2	2.2	60.3	2.3	61.0	2.3	65.0	2.0	74.9	2.0	84.9
5	2.4	35.9	2.2	44.1	2.1	63.4	2.1	62.7	2.0	69.0	2.0	75.3	1.8	86.3
6	2.2	36.2	2.0	43.7	1.9	65.4	1.9	67.4	1.9	69.7	1.9	78.4	1.9	84.9
7	2.4	35.7	2.3	42.8	2.3	62.3	2.3	60.4	2.3	63.6	2.1	76.1	2.0	82.9
8	2.2	36.6	2.1	43.9	1.9	65.0	1.8	68.2	1.8	71.2	1.8	79.9	1.8	86.8
9	2.2	37.0	2.1	44.2	2.0	66.1	1.9	69.1	1.9	73.0	1.9	80.1	1.9	84.9
10	2.2	37.7	2.1	45.0	2.0	64.9	2.0	60.2	2.0	68.2	1.9	79.4	1.9	85.2
11	2.4	35.3	2.2	43.7	2.2	59.8	2.3	58.7	2.2	63.4	2.0	74.2	2.0	84.9
12	2.1	36.8	2.0	43.8	1.9	60.1	1.9	64.6	1.9	69.8	1.8	79.9	1.8	85.3
13	2.0		1.6		1.4		1.4							
14	2.4	35.2	2.2	42.6	2.0	64.2	2.0	63.7	2.0	67.9	1.9	78.4	1.9	84.4
15	2.6	33.8	2.2	45.0	2.2	60.1	2.0	60.2	2.1	65.8	2.0	77.3	2.0	83.9
16	2.4	34.9	2.3	44.2	2.2	59.9	2.3	61.0	2.2	66.6	2.0	77.6	2.0	85.1

week. For instance, in mixtures 8 and 10 the proportion of available phosphates was well above 17 per cent. At the end of the fifth week the increases in the amounts of available phosphoric acid over those found at the end of the third week were not large. On the other hand, a very marked increase occurred between the end of the fifth and the end of the sixth week. For instance, in mixtures 5 and 10 there were found at that time 30 per cent of the phos-

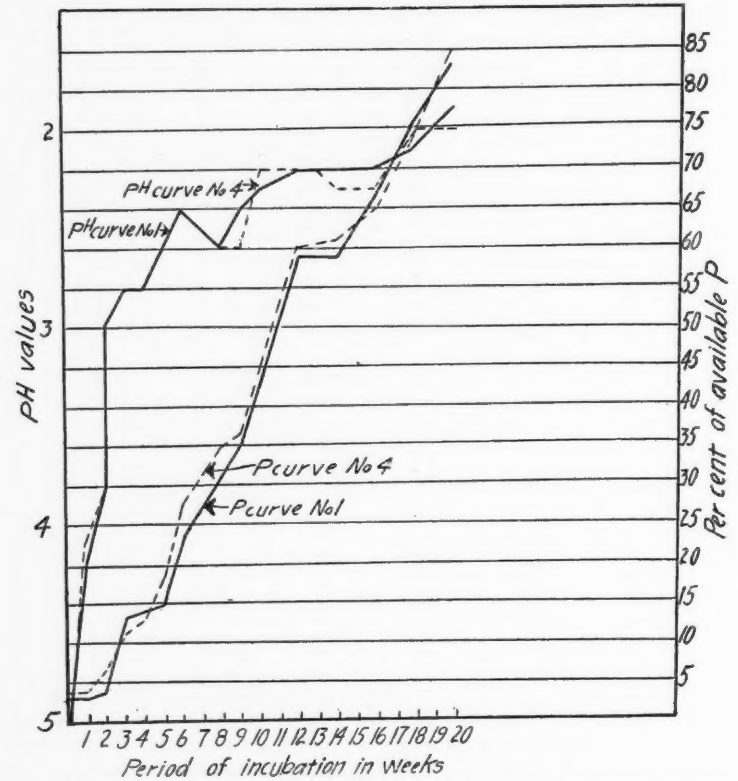

FIG. 1. CURVES OF HYDROGEN-ION CONCENTRATION AND PER CENT OF AVAILABLE PHOSPHORIC ACID AS P IN SAMPLES 1 AND 4

phoric acid in an available form. Progressive and marked increases occurred at the end of the eighth, ninth and tenth weeks. A very marked increase occurred again between the end of the tenth and that of the twelfth week. This continued until the end of the twentieth week when the proportion of available phosphoric acid was above 82 per cent in all cases and in at least two instances well above 86 per cent.

In attempting to interpret the data just given one should bear in mind that the pH determinations record the intensity of the acid rather than the quantity of it. As time went on the quantity of sulfuric acid or of acid sulfates accumulating in the mixtures gradually increased. There was, therefore, a gradu-

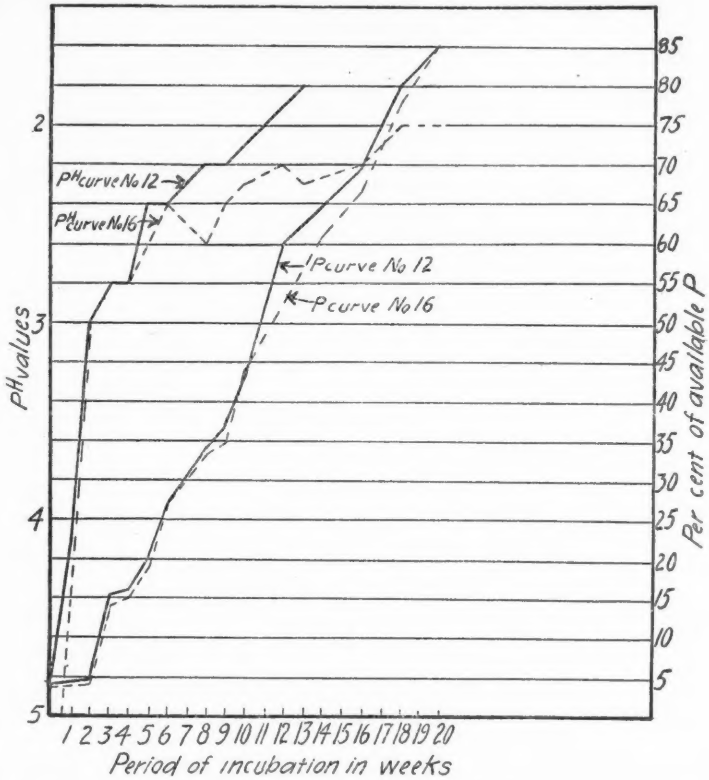

FIG. 2. CURVES OF HYDROGEN-ION CONCENTRATION AND PER CENT OF AVAILABLE PHOSPHORIC ACID AS P IN SAMPLES 12 AND 16

ally increasing quantity of acid material available for reacting with the tricalcic phosphate. Figures 1 and 2 show in a graphic way the progressive changes in mixtures 1, 4, 12 and 16. It is expected that other data now available, and confirming the results recorded in this paper, will be made ready for publication in the near future.

CONCLUSIONS

This set of experiments shows no advantage in starting with a relatively high hydrogen-ion concentration through additions of sulfuric acid. On the other hand, there is evidence that such advantage may be had in mixtures of a different composition. The data in question will be reported at a later date.

REFERENCES

(1) Clark, W. M., and Lubs, H. A. 1917 The colorimetric determination of hydrogen-ion concentration, and its application in bacteriology. *In* Jour. Bact., v. 2, p. 1–34.

(2) Gillespie L. J. 1916 The reaction of soil and measurements of hydrogen-ion concentration. *In* Jour. Wash. Acad. Sci., v. 6, p. 7–16.